Vol. XCVI. No. 4. July–August, 1959

GEOLOGICAL MAGAZINE

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THE UNIVERSITY OF MICHIGAN

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STEPHEN AUSTIN & SONS, LTD.
CAXTON HILL, WARE ROAD, HERTFORD, HERTS

SUBSCRIPTION 45/- PER ANNUM

GEOLOGICAL MAGAZINE

founded in 1864

by the late Dr. H. Woodward, F.R.S., with which

is incorporated

THE GEOLOGIST

(founded 1858)

Published every two months price 45/- per annum.
(single numbers, 10/-).

Subscriptions for 1959, inquiries relating to back stock, advertising, etc., should be sent to Stephen Austin & Sons, Ltd., Caxton Hill, Ware Road, Hertford, Herts.

The Editors are directed to make it known to the public that the authors alone are responsible for the facts and opinions contained in their respective papers and for the correctness of their references.

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GEOLOGICAL MAGAZINE

VOL. XCVI. No. 4. JULY–AUGUST, 1959

Issued 7th August, 1959

On the Basis of Pleistocene Correlation in East Africa

By RICHARD FOSTER FLINT

ABSTRACT

The scheme currently used in East Africa for Pleistocene stratigraphic correlation is based on climate. This basis is thought to be undesirable because it consists of second-order concepts rather than of primary, objective units and because its unconventional character inhibits correlation between East Africa and other regions. Furthermore the conceptual sequence of pluvial and interpluvial Pleistocene climates is not fully supported by the field evidence described thus far. Local support exists for the Gamblian and post-Gamblian wet climates, and at one locality a wet phase of pre-Gamblian age is admissible. The other units of the current scheme require factual support before they can be accepted. It is suggested that a more conventional basis of Pleistocene correlation in East Africa is desirable.

I. INTRODUCTION

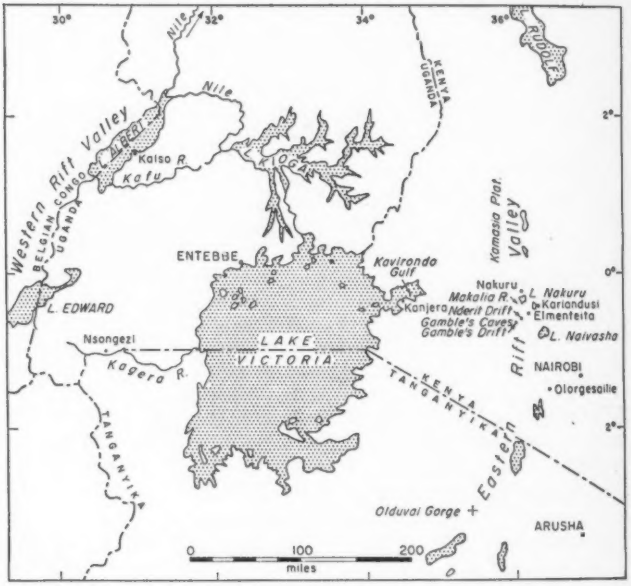
DURING a visit to East Africa in 1957, in the course of which I had opportunity to examine many Pleistocene sections described or discussed in the literature, I came to the opinion that although parts of the stratigraphic scheme now in general use in that region are well founded, the scheme as a whole, in its present form, is not fully supported by the field evidence and should be re-examined. Soon after leaving East Africa, I learned that an opinion similar in some respects had been reached by Dr. H. B. S. Cooke of the University of the Witwatersrand, Johannesburg. Later he courteously lent me a manuscript (subsequently published: Cooke, 1958), that deals with some aspects of the subject. I recommend his paper strongly to those who take an interest in the Pleistocene stratigraphy of Africa.

The scheme in current use (Table 1) is based on inferred former climates, designated as Pluvial and Interpluvial, and considered to have alternated throughout Pleistocene time.[1] Examination of the scheme suggests two questions. First, are the climatic units based on adequate evidence? Second, is climate a desirable basis for a stratigraphic classification? I propose to discuss each question in turn.

[1] These terms and their implications are discussed in Flint, 1959.

II. Analysis of the Climatic Units

In examing the evidence on which the currently used scheme has been erected, we must first consult the literature for names and descriptions of units and for statements of the field data set forth in support of them. In Table 1, column 4 shows a recent reconstruction of climatic changes in East Africa. Columns 1, 2, and 3 reproduce representative earlier arrangements, in order of publication date. From the table the evolution of the existing nomenclature can be inferred. In the following



Text-fig. 1.—Sketch-map showing localities and features mentioned in the text.

discussion published descriptions are noted wherever they are known to exist.

A. *Pluvials*

Nakuran is the name given by Leakey and Solomon (1929) to a post-pluvial wet period. Solomon (1931, p. 246) referred to it as an " epi-pluvial of minor importance " following the Makalian. It seems to have been named for the lake, basin, or town of Nakuru, Eastern Rift Valley, Kenya, for Leakey (1929) stated that it is " connected with the old 185 feet beach of Lake Nakuru ". Later it was said to be

represented by a strandline 145 feet above L. Nakuru and by layer 3 in the stratigraphic sequence in the floor of Gamble's Cave II, near Lake Nakuru (Leakey, 1931, p. 12, 94, 243). The implication is that the Nakuran was a time when Lake Nakuru was much larger than at present, a fact that had been established by Nilsson (1929). As non-climatic controls of the level of this lake seem very improbable, the Nakuran climate can be accepted as probably wetter, or cooler, or both, than the climate of to-day.

The Makalian Post-Pluvial Wet Phase was named for the Makalia River south of Lake Nakuru, Kenya (Solomon in Leakey, 1931, p. 246). It is represented by layers 5, 6, and 7 in the Gamble's Cave II stratigraphic sequence (Leakey, 1931, p. 93) and by a strandline 375 feet above Lake Nakuru (*idem*, p. 12). The strandline, recording as it does a deep lake in a closed basin, is acceptable evidence of a climate wetter than to-day's.

The Gamblian Pluvial was named for Gamble's Cave II and Gamble's Drift, near Elmenteita, Kenya (Solomon in Leakey, 1931, p. 246). The *Upper Gamblian* is represented by layers 9 to 14 in the Gamble's Cave II sequence (Leakey, 1931, p. 93) and by a strandline [1] 510 feet above Lake Nakuru (*idem*, p. 12), although the basis of correlation of the strandline with the cave layers is not made wholly clear. The *Lower Gamblian* is represented by a lake beach described as being 700 feet above Lake Nakuru (*idem*, p. 12).

Upper and Lower Gamblian, Pluvials separated by a less pluvial climate, were inferred also from lake-floor sediments and a disconformity exposed in the Naivasha and Nakuru basins (Solomon in Leakey, 1931, p. 246, 248–249, 255, 259). Presumably these were correlated with the cave sequence on cultural evidence. According to Cole (1954, p. 49), the Gamblian Pluvial was later considered to have consisted of three lake maxima rather than two, based on evidence (not specified) at Nderit Drift and other areas in the Nakuru Basin. These later subdivisions are shown in Table 1, column 4.

In the Gamble's Cave II sequence, evidence of a pluvial consists of layer 15, the beach sediment (pumiceous sand and gravel with fossil gastropods [Connolly in Leakey, 1931, p. 276–277]). The same beach occurs elsewhere in the Naivasha and Nakuru basins and implies a former large deep body of water, for the presence of which a climate moister and probably cooler than to-day's is the most reasonable explanation. The Gamblian, or rather Upper Gamblian, at its type locality therefore appears to represent a pluvial climate and is named for a feature that is associated with such a climate.

In the Olduvai Gorge, Tanganyika, however, the Gamblian Pluvial

[1] Later the strandline was considered by Leakey to be of Middle Gamblian age (L. S. B. Leakey, unpublished communication).

is held to be present also, represented by a wide, mature valley (Leakey, 1951, p. 26; Reck in *idem*, p. 7). A climate wetter than to-day's is inferred on the ground that under to-day's strongly seasonal climate, streams cut steep-sided gorges rather than wide mature valleys. This basis of climatic inference is questionable in that the widths of valleys and the angles of their side slopes depend mainly on the relation between rate of downcutting by streams and rate of slope erosion by weathering, mass-wasting, sheet runoff, and gullying. The relationship is determined by such factors as crustal movement, lithology, and

TABLE 1.—CHART SHOWING SELECTED CLIMATIC SEQUENCES IN EAST AFRICA

Column 1 (Leakey and Solomon 1929, p. 9)		Column 2 (Leakey 1931, p. 12; see also Solomon in idem, p. 245)		Column 3 (Wayland 1934, p. 344)		Column 4 (Leakey 1948, p. 83)
Old names	New names	The climatic changes of the Pleistocene in Kenya		Climatic periods		Climatic changes in East Africa
Post-Pluvial wet period	Nakuran†	Nakuran		Post-Pluvial	Nakuran	Nakuran 2[d] Post-Pluvial Wet Phase
3[d] Pluvial	Makalian	Makalian			Makalian	Makalian 1[st] Post-Pluvial Wet Phase 1[st] Post-Pluvial Dry Phase
2[d] Pluvial	Gamblian	Second major pluvial	Upper Gamblian		Part 2	Gamblian 3[e] Recession 4[th] Pluvial 2[e] Recession 1[e]
1[st] Pluvial	Enderian		Lower Gamblian			
		Dry period		Pluvial II	Intra-Pluvial Oscillation	3[d] Interpluvial
0[th] Pluvial		First major pluvial	Kamasian		Part 1	Kanjeran 2[e] Recession 3[d] Pluvial (Formerly called Upper Kamasian)
						2[d] Interpluvial
						Kamasian 2[d] Pluvial (Formerly called Lower Kamasian)
				Interpluvial		1[st] Interpluvial
				Pluvial I	Part 2	Kageran 1[st] Pluvial
					Intrapluvial Oscillation	
					Part 1	

†Spelled Nakurian in Leakey 1929, p 751.
*Numbers denote pluvial maxima.

attitude of rocks, climate, and time. Climatic change cannot be confidently regarded as the cause of a particular change in valley form, without detailed analysis of the factors contributing to the local morphology. Hence, whereas change to a wet climate cannot be ruled out as the cause of the morphology of the Olduvai Gorge, it can hardly be said, in the present state of knowledge, to support the concept of a Gamblian Pluvial in that locality.

The Kamasian Pluvial was named by extending the name Kamasia, given by J. W. Gregory (1921, p. 114) to a former lake to which he ascribed sediments in the Eastern Rift Valley, to refer to a pluvial climate (Leakey, 1931, p. 11; Solomon in *idem*, p. 245). Gregory's type area is the Kamasia Plateau east of the Rift Valley, between the latitudes of Nakuru and Eldoret; he recognized correlative sediments in other areas.

The basis on which the Kamasian sediments of Gregory are believed to indicate a pluvial climate is not entirely clear. The sediments to which this name was applied indirectly consist of tuffaceous sand and silt, volcanic gravels, and diatomite, exposed at various places in the sides and floor of the Rift Valley. Commonly the sediments are parallel bedded. At least some of them antedate substantial faulting and tilting, which in turn antedate the lacustrine features correlated with the Gamblian. Gregory (1921) believed their age to be Miocene. These sediments were held to be the record of " one enormous lake " at least 120 miles long (Solomon in Leakey, 1931, p. 246). Presumably it is the presence of the inferred lake that was believed to require a pluvial climate for its maintenance. There are two obstacles to accepting the implication, if that is the basis of the belief. The first is that firm correlation of the tuffaceous sediments exposed at various localities in this sector of the Rift Valley has not yet been published; hence it is not sure that one large lake is represented. It appears possible, at least, that the sediments in question represent various basins, perhaps no larger than the basins of the existing Lakes Naivasha and Nakuru, and that the sediments are of various pre-Gamblian ages. As the tuffs in this segment of the valley are megascopically much alike, detailed study of them would probably be needed to determine whether they were deposited contemporaneously in a single large basin or in two or more basins, perhaps at different times.

The second obstacle is that even should the concept of a single large lake be well established, its implication as to a former pluvial climate might not be. Downfaulting of the order of 2,000 feet has occurred since some of the tuffs were deposited. Data, admittedly scattered, suggest that in this part of the Rift Valley mean annual rainfall increases by about 1 inch for every increase of altitude of 150 to 200 feet. On this basis, restoration of the pre-faulting altitude should increase the rainfall from around 20 inches (the rough present value for the valley floor near Lake Naivasha) to more than 30 inches, under the existing climatic regimen. If this line of reasoning is valid, it is not apparent that the lacustrine character of the tuffs constitutes evidence of a pluvial climate, as the inferred lake might have been wholly or partly the result of rainfall appropriate to a former higher altitude.

Some of the tuffs mentioned above, and formerly correlated with the Kamasian, were subsequently considered to belong to a separate pluvial called Kanjeran. However, the validity of the physical evidence for the inference as to a pluvial climate remains unaffected by the change.

The Kanjeran Pluvial was named for sediments exposed at Kanjera, on the south side of the Kavirondo Gulf, on the Kenya coast of Lake Victoria (Leakey, 1951, p. 26; 1952). Apparently the Kamasian

Pluvial proposed in 1931 had come to be regarded as consisting of two wet periods separated by a dry period. This is implicit in the 1948 chart published in 1950 (Table 1, column 4), but I have not found an earlier published use of the terms Upper Kamasian and Lower Kamasian, although Leakey (1936, fig. 1) listed two maxima of the Kamasian Pluvial. The name Kanjeran Pluvial was substituted for Upper Kamasian (Pluvial) in 1950 (Leakey, 1950, p. 169). This change appears to have resulted not from further study in the type area of the Kamasian Pluvial, but from stratigraphic and faunal relations at Kanjera and at still a third locality, the Olduvai Gorge in Tanganyika. Both the diatomites and tuffs at Kariandusi near Nakuru and the lacustrine deposits exposed at Kanjera contain Acheulean hand axes; on this basis the two sedimentary bodies are correlated (Cole, 1954). The sediments at Kanjera in turn are correlated with Bed 4 in the sequence exposed in the Olduvai Gorge, on a basis of culture and of fossil mammals (Leakey, 1951). Hence a pluvial based on evidence of an ancient lake in the Eastern Rift Valley region is correlated with and named for sediments at Kanjera, for which, although they contain similar artifacts, no pluvial climate has been established[1]; these sediments in turn are correlated with strata in Tanganyika which are lacustrine and are considered in consequence to be pluvial. However, the strata in Tanganyika occupy an area that may have been subject to gentle deformation. Furthermore, there have been identified no strandlines, such as occur in the Naivasha-Nakuru district, from which fluctuation of lake level independent of crustal movement can be inferred. Hence it is apparently not excluded that the lake in which the strata took form was controlled by tectonics rather than by climate.

With regard to the faunal correlation between Kanjera and Olduvai, Cooke (1958) noted that the fossils at Kanjera and in Bed 4 at Olduvai are of kinds of animals that have long stratigraphic ranges and that hence are of little value for correlation.

The Kamasian (formerly Lower Kamasian) sediments of the type area are correlated with Beds 1 and 2 at Olduvai (Leakey, 1951, p. 30), but as the former contain neither fossils nor artifacts the correlation can hardly be firm.

According to Cole (1954, p. 47) lacustrine sediments at Olorgesailie, Kenya, are correlated with the Kanjeran pluvial, apparently because they contain Acheulean implements like those at Kanjera and at Kariandusi. As the implements represent a culture substantially older than those in the strata associated with the Gamblian Pluvial, the

[1] The sediments are mainly lacustrine, and lie on the shore of Lake Victoria, at an altitude only about 50 feet higher than the surface of the lake. Kent (1942) described them under the name of Kanjera beds. He held (p. 131) that they were laid down during a pluvial period, but offered no supporting evidence.

Olorgesailie lake can reasonably be referred to a pre-Gamblian time. The exposed sequence of lake sediments includes no fewer than seventeen erosional unconformities (Cole, 1954, p. 142), testifying to repeated fluctuations of lake level. Furthermore, to-day's rainfall is estimated at only 18–20 inches, and the watershed to the lake area (it is no longer a basin, having been disrupted by faulting) is small. Consequently, it seems probable that, in order to maintain the lake, greater rainfall than this (or lower temperature, or both) would have been needed. On this reasoning, both the existence and the fluctuation of the lake favour a pre-Gamblian climate, over the Olorgesailie watershed, that was moister than to-day's.

The Kageran Pluvial was named for the Kagera River in Uganda. The name was given at some time prior to 1948, because it appears in a chart of that date (Leakey, 1948, p. 63). According to Cole (1954, p. 44), evidence of this pluvial consists of a terrace at a height of 270 feet above the Kagera River; the terrace gravel contains pebble tools. No fossils have been found in the gravel. The only argument I have been able to find in the literature, claiming to support the concept of a pluvial climate at the time the gravel was deposited, is the statement that at the close of the Pliocene epoch, during which the climate had been arid, streams were rejuvenated, " and in times of deposition their discarded loads were correspondingly larger " (Wayland, 1934, p. 345, 347). Presumably this means that the terrace gravel was thought to have been deposited by a Kagera River more competent, and therefore having a greater discharge, than the Kagera of to-day. But the caliber of the bed load of a stream depends on several factors, only one of which is discharge. Furthermore, if one judges from the bars exposed, in June, 1957, along the Kagera in the vicinity of Nsongezi, the locality near which the terrace gravel was reported (Wayland, 1935, p. 70; Lowe, 1952, pl. fol. p. 24; Solomon in O'Brien, 1939, p. 36), the river recently has been moving rock particles not greatly different in caliber from the coarsest alluvium exposed in its terraces.

No detailed description of the terrace gravel on which the concept of the Kageran Pluvial appears to depend has been published, nor, as far as I know, has a full statement of the climatic inference to be drawn from the gravel. Pending the publication of both evidence and inference, the term Kageran Pluvial should be regarded as insecurely established. Its use meanwhile is likely to mislead those unfamiliar with the problem. Whether the gravel exposed in the Kagera Valley can be correlated with sediments elsewhere is doubtful. As stated above, it contains no fossils. It does contain at least some pebble tools. Although some may question whether all the pebbles collected (see Lowe, 1952) are indeed artifacts, rather than rock fragments

rounded and subsequently fractured by the Kagera River itself, the validity of the objects that survive such scrutiny, for use in stratigraphic correlation, can be assessed only by prehistorians expert in such matters.

B. *Interpluvials*

The word interpluvial is employed here because it has been generally used in the literature since at least as long ago as 1934. It should be noted, however, that the word implies that any relatively dry climate it refers to was both preceded and followed by relatively wet climates. Until firmer inferences have been drawn from the sequence of Pleistocene features, *nonpluvial* would seem to be a more appropriate term for a climate inferred to have been drier than a climate immediately preceding or following it.

The 1st Interpluvial seems to have been introduced into the sequence by Wayland in 1934, in a chart here reproduced in Table 1, column 3. The evidence is stated (Wayland, 1934, p. 347) to be derived from the Kaiso beds in the Lake Albert basin, a part of the Western Rift Valley. The strata are said to record two lacustrine sequences separated by evidence of desiccation. Apparently the concept of desiccation consists of " bone beds " near the top of the exposed sequence. These are lenticular ironstones, locally oolitic, interpreted as bog iron ore developed in pools within an area in which a more extensive lake had formerly existed (Wayland and others, 1926, pt. 1). Further evidence of desiccation is said to be the presence of gypsum in the sediments. The " bone beds " contain very early Pleistocene vertebrates.

On 29th May, 1957, I visited the type locality at Kaiso with Dr. W. W. Bishop of the Uganda Geological Survey. We collected fossil gastropods, fishes, turtle, crocodile, hippopotamus, elephant, and unidentified coprolites, from the " bone beds " at about 60 feet above Lake Albert. To the extent that the " bone beds " suggest emergence of the area from a lake, I agree with Wayland (1934, p. 347) that such emergence could have resulted solely from movement of the very unstable floor of the Rift Valley, but I have to disagree with Fuchs (1934, p. 146). From ironstone lenses, gypsum, and calcareous nodules in the upper part of the Kaiso beds, he inferred a climate that was becoming increasingly arid, but offered no discussion of the evidence. In my opinion, all that can be reasonably inferred from published knowledge of these features is emergence, which could have resulted as well from crustal movement, decanting a former lake, as from climatic change. As long as crustal movement is not eliminated as a possible cause of emergence, doubt must attach to the concept of an " interpluvial " climate during the time of deposition of the Kaiso " bone beds ". As no artifacts have been found in these beds and as no fossils have been found in those terrace gravels of the Kagera River on which the

Kageran Pluvial concept is based, there seems at present to be no reliable means of determing the stratigraphic relations or relative age of the two groups of sediments.

The 2nd Interpluvial was introduced into the scheme at some time prior to 1948, when it seems first to have appeared in published form (Table 1, column 4). It is based on the occurrence, in the sequence exposed in the Olduvai Gorge, Tanganyika, of Bed 3, a red bed, between Beds 2 and 4 which are not red (Leakey, 1951, p. 25–30; Leakey, 1952). Beds 2 and 4 are mainly lacustrine; the red Bed 3 is mainly fluvial. Hans Reck, who described the Olduvai stratigraphy, ascribed Bed 3 to deposition under an arid climate, but did not discuss the question further. When I visited the Olduvai Gorge in June, 1957, with Dr. L. S. B. Leakey, Mr. Brian Baker, and Dr. Philip Tobias, Bed 3 appeared to me to be alluvium washed into a basin of deposition as reworked lateritic "red-earth" soil developed from volcanic materials such as occur in the adjacent volcanic highlands. A suite of samples was collected for analysis by the Uganda Geological Survey, but the results are not yet available. A cellular, gossan-like zone at the top of the bed appeared to have resulted from local alteration, by surface or subsurface water, accompanied by renewed movement of ferric iron.[1]

At the period of Reck's studies at Olduvai (1913; 1931), red beds were rather generally regarded as indicative of aridity, perhaps because of the association of some of them with evaporites and of others with eolian sediments. However, as a result of more incisive studies since then, opinion has changed. Red sediments have come to be attributed to the protection of sediments, initially red, from reduction after deposition. The ferric oxide is considered to be in most cases an original constituent of the sediments, brought into the basin of deposition by streams from areas where red soils were being eroded. Such soils imply moist climates, ordinarily with markedly seasonal rainfall.[1] The moist climate pertains, of course, to the area of erosion and not to the basin of deposition. Hence the red colour of Bed 3 would not in itself support the inference of any particular kind of climate at the time and place of deposition. It is true that Bed 3, being mainly alluvial, indicates an episode of emergence intervening between two episodes of basin lakes represented by the lacustrine Beds 2 and 4. But the emergence, although conceivably of climatic

[1] An unpublished memorandum written by Professor F. E. Zeuner, and received after this paper was written, reaches a similar conclusion on the basis of a visit to the locality followed by laboratory examination of samples. The movement of iron during weathering of Bed 3 is held to indicate a moist climate at the time and place of weathering.

[1] An excellent summary of current views on the origin of red beds, with bibliography, is given by Dunbar and Rodgers (1957, p. 209–218).

origin, does not necessarily demand a climatic cause, for the possibility has not been excluded that emergence did not result from crustal movement. Nor does the inception of the lake basin demand climatic change, inasmuch as the possibility of damming by volcanics and crustal movement are not excluded by the evidence reported thus far.

The Rawe beds of Kent (1942), occurring near Kanjera, were believed by him to have been laid down in an interpluvial time (Kent, 1942, p. 124, 131–132). He cited as evidence of intermittent desiccation: (*a*) Lamination, suggesting seasonal sedimentation; (*b*) Gaylussite pseudomorphs, indicating at least local strong concentration of carbonates; (*c*) Fish beds. The Rawe beds of Kent have been placed (with the name Upper Rawi Beds) in the Kamasian-Kanjeran climatic interval (Cole, 1954, p. 60), correlative with Bed 3 of the Olduvai sequence. It is difficult to see what support the three features, cited above, give to the hypothesis that the sediments in question are the record of an interpluvial climate.

We come next to the 3rd Interpluvial. The literature contains a number of references to a dry climate intervening between Kanjeran time and Gamblian time, but affords little or no supporting evidence. According to Wayland (1934, p. 348), this dry time (his Intra-Pluvial Oscillation (Table 1, column 3)), was accompanied by marked reddening of soils and lateritization, exposure and weathering of lake sediments, and intercalation of " talus " between layers of alluvium and lacustrine sediments. No localities or details are cited except for the " talus ", which is shown to occur at Nsongezi on the Kagera River, Uganda, and which is discussed further (Wayland, 1935) under the name of M-Horizon. The development of that horizon is said (p. 69) to have been accompanied by ferruginization and preceded by sustained decreased precipitation. The former inference is based on the concept that red sediments result from aridity (p. 73); the latter on the obvious fact that the M-Horizon represents a land surface created by the emergence of lacustrine sediments (p. 69). The sequence in which the M-Horizon [1] occurs is rich in artifacts, and on the basis that no significant change in culture occurs at this horizon, O'Brien (1939, p. 296–307) concluded that the span of time it represents is far too short for an interpluvial, but agreed on cultural evidence that the climate was then dry enough to have driven Acheulean man away from the locality.

Having visited Nsongezi in June, 1957, with Drs. W. W. Bishop and Merrick Posnansky, and having examined the excellent exposures of the M-Horizon there, I would add the opinion that the M-Horizon

[1] Other horizons, designated N and O by Wayland, are not discussed here because they have not been made the basis of climatic inference.

appears to be a pebble lag, the result of eluviation of a gravel, possibly part of a small fan, on a gently sloping terrace surface. Human occupation seems to have resulted in the mixing of cores and flakes possessing prepared striking platforms, with natural pebbles. No clear indication of the climate prevailing at the time was evident.

In the (Wayland, 1935 and O'Brien, 1939) references, the relation of the sequence at Nsongezi to the history of Lake Victoria is discussed. One of the possibilities is that the fine sediments, mainly clayey silt, underlying the M-Horizon were deposited in an arm of an enlarged Lake Victoria that backed up the Kagera Valley and flooded the Nsongezi area. But the subsequent emergence need not have resulted from climatic desiccation; it could have been the result of crustal movement. Detailed study of the sediments in the Kagera River valley between Nsongezi and the river mouth will be necessary before the question can be answered. Meanwhile the demand for a dry climate at the time of formation of the M-Horizon, although not ruled out, does not seem compelling.

The 3rd Interpluvial is said to be represented also in the Olduvai Gorge sequence, by the unconformity at the top of Bed 4, a lacustrine unit. The top of the bed is held to mark the disappearance of the Olduvai Lake, primarily because of crustal movement and secondarily because of climatic desiccation (Reck in Leakey, 1951, p. 19). Here, too, climatic change, although admissible, does not seem to be demanded by the facts appealed to.

The first Post-Pluvial Dry Phase is said (Leakey, 1929, p. 751; 1931, p. 11) to have been accompanied by desiccation of lakes in the Naivasha sector of the Eastern Rift Valley, by the development of reddish soil on all exposed land surfaces and by the deposition of wind-blown sand. The features cited are layer 8 (red wind-blown sand) in the floor sequence of Gamble's Cave II (Leakey, 1931, p. 116), sediments in the Makalia Valley (Solomon in *idem*, p. 250, 255), and wind-blown sand in the Olduvai Gorge, postdating the cutting of a wide valley and antedating the trenching of a narrower one (Leakey, 1931, p. 16; 1951, p. 26; Reck in *idem*, p. 7).

Although not compelling evidence of a dry climate, for it forms in special situations to-day under moist climates, wind-blown sand in the localities named could reasonably have resulted from reduced rainfall and perhaps higher temperatures, and can be accepted provisionally as indicating climatic drying.

The same is not true of the development of reddish soil, which, as mentioned in the discussion of Bed 3 at Olduvai, is more likely to record a moist seasonal climate than a dry one.

The evidence of desiccation in the Makalia Valley, apart from the occurrence of red soil, was not stated by Solomon specifically.

TABLE 2.—CHART SHOWING TYPE AREAS OF CLIMATIC PHASES, STRATIGRAPHIC CHARACTERISTICS IN TYPE AREAS, AND CORRELATIVES ELSEWHERE IN EAST AFRICA. ASSEMBLED FROM THE LITERATURE. ARROWS INDICATE SPECIFIC BASES OF CORRELATION.

Name of climatic phase	Stratigraphic characteristics in type area *		Correlatives				Olduvai Gorge
Nakuran Pluvial	Strandlines Lake-floor sediments	NV					
Dry phase (unnamed)	Eolian sand	NV					
Makalian Pluvial	Strandlines Lake-floor sediments	NV					
1st Post-Pluvial Dry Phase	Eolian sand	NV					Eolian sand
Gamblian Pluvial	Strandlines Lake-floor sediments with unconformities	NV					
3d interpluvial	Reddish soil, pebble lag, emergence	NS					Unconformity at top of Bed 4 (emergence)
Kanjeran (Upper Komasian) Pluvial	Lake sediments Fossil vertebrates without climatic implication *Acheulean culture*	KN	Lake sediments at Kariandusi *Acheulean culture*		Lake sediments at Olorgesailie Fossil vertebrates without climatic implication *Acheulean culture*		Bed 4 (Lake sediments) Fossil vertebrates without climatic implication *Acheulean culture*
2d Interpluvial			Rose beds of Kent at Konam including laminations & gypsiferous pseudomorphs				Bed 3 Red color Alluvial, at least in part
Komasian (Lower Komasian) Pluvial	Lake sediments in Eastern Rift Valley without fossils or assemblages of artifacts						Beds I & 2 (Lake sediments) Fossil vertebrates without climatic implication
1st Interpluvial	"Bone beds" (lake or swamp sediments) Emergence. Fossil vertebrates without climatic implication	KS					
Kageran Pluvial	Stream gravel without fossils *Pebble tools?*	NS					

* Type areas: KN—Kanjera; KS—Kaiso; NS—Nsongezi district; NV—Ndivosha sector, Eastern Rift Valley.

Presumably it consists of an unconformity occurring between two bodies of lake-floor sediment. Emergence would be a better word to use here than desiccation, for the latter word now carries climatic implications, whether intended or not. All that can be inferred from the unconformity, if it is the evidence implied and if related and more compelling features are not cited, is emergence. As stated in connection with sediments at Kaiso and at Olduvai, evidence of emergence alone

does not demand climatic change as long as crustal movement and volcanic activity are not excluded as alternative causes. On the other hand the lake strandlines in the district, by excluding these two causes, afford more convincing evidence of climatic change than does an unconformity alone. Being nearly horizontal, and postdating local volcanic activity other than the deposition of ash, these features seem to demand climatic desiccation as the cause of lacustrine shrinking, when they are considered in conjunction with the unconformities in the sequence of lake sediments beneath the floors of the basins in which they occur. Surprisingly, they do not seem to have been cited specifically in the literature as supporting the concept of a drier time between the Gamblian and Makalian wetter periods.

The dry phase intervening between the Makalian and Nakuran Wet Phases is represented by red eolian sand in the Gamble's Cave II sequence (Leakey, 1931, p. 94, 116, layer 4). This sand affords climatic implications similar to those which attach to layer 8, discussed above.

C. *Summary*

Summarizing the discussion in the foregoing section and drawing attention to Table 2, which shows the case for the climatic sequence in condensed form, we can say that the presence of strandlines and floor sediments of lakes within closed basins, and for the control of which causes other than climate seem not admissible,[1] constitutes good evidence of former moister, and very likely also cooler, climate within the general bracket of Gamblian time. Whether all the "wet" and "dry" phases (five in the Gamblian and five more in the post-Gamblian), specified in the sequence shown in Table 1, column 4, are admissible on the evidence published so far is less clear. Wind-blown sand, although it does not in itself demand the concept of dry phases, is admissible at least provisionally because of its stratigraphic relation to the lake features. Published data on the Gamblian and later climatic evidence are, however, so inadequate that the number of climatic fluctuations to be read from them is uncertain.

The only pre-Gamblian climatic phase that seems to find even moderate support is the pluvial at Olorgesailie, where the critical sediments are ascribed, on the basis of artifacts, to the Kanjeran.

The other pre-Gamblian climatic phases, from Kageran to 3rd Interpluvial inclusive, and including the Kanjeran as represented elsewhere than at Olorgesailie, are not well supported by acceptable evidence of the kinds of climates claimed for them. This statement is not meant to imply that some of the phases may not have been

[1] Apart from reconnaissance observation by J. W. Gregory, study of these features and recognition of their climatic significance is primarily the work of Nilsson (1929, and later publications not listed here because they make no major changes in the results set forth in the 1929 paper).

characterized by the kinds of climates ascribed to them in the literature. It implies only that the evidence specifically appealed to does not seem to demand such climates, and that stronger evidence is needed before the phases should be accepted without question.

The acceptable evidence, embracing the general concept of relatively moist Gamblian and post-Gamblian climate, with an unspecified number of fluctuations, comes mainly from a single segment of the Eastern Rift Valley in Kenya. Hence in itself it does not justify the inference that such climatic phases simultaneously affected the whole of East Africa or even wider regions of the continent. However, unpublished data on lake features in closed basins (see summary in Flint, 1959) extend the probability of such fluctuation along the Rift Valley into Tanganyika on the south and, in the opposite direction, into northern Kenya. Likewise, the lowering of Lake Victoria tentatively inferred from biologic data (see summary in Flint, 1959) seems acceptable evidence of climatic fluctuation, provided lowering of the lake outlet can be eliminated. At least a start has been made, therefore, in assembling evidence in support of the reasonable assumption that successive climatic changes have affected a wide region in Africa.

Examination of the "pluvial hypothesis" in terms of features observed in Uganda led Solomon and O'Brien (O'Brien, 1939, p. 6–10, 40–42, 292–293) to "discard it completely as a basis for the classification of the African Quaternary". I agree that as far as the Uganda data pertaining to evidence of pre-Gamblian "pluvials" are concerned, their opinion is justified. But I would not go as far as they did (*idem*, p. 40) in throwing out, in their disillusionment with the Uganda reconstruction, the Gamblian climatic phases in Kenya. As we have seen, the evidence there supports the concept of former moister climates.

The conclusion that in East Africa so far we have reasonably sound evidence of no more than two major pluvial climates (Gamblian and late pre-Gamblian) is not surprising. Sediments and other geologic features of late date are generally better preserved, more widely exposed, and easier to interpret than those of earlier date. In Europe and North America, the events of the last glaciation are far better understood than those of the preceding ones, for just these reasons. Continued patient work, with close attention to detail, should result in data from which our knowledge of the climates of pre-Gamblian times can be inferred with greater confidence.

Let us turn now to the merits of climate as the basis of a stratigraphic system.

Climate as the Primary Basis of a Stratigraphic Scheme

Our system of Pleistocene geologic stratigraphy and indeed geologic

stratigraphy as a whole, as distinct from cultural stratigraphy, has been built up on a basis of layers of rock or sediment, defined and described, and correlated from one place to another by means of the fossils they contain. The system is eminently convenient and has the sanction of long-continued and almost worldwide use. It should not be replaced in any region unless it is shown that the substitute possesses superior merits.

So far as I am aware, such merits have not been shown for the climatic scheme. That scheme has not been described nor explained as a system; it seems to have grown up little by little, reaching its existing status in default of contrary opinion. Table 1, column 4, looks like an ordinary correlation chart, and has been mistaken for one by workers outside East Africa. Yet it is not an ordinary chart, because the names appearing on it are those of climates inferred to have succeeded each other in time. The names, therefore, must represent, not the objective realities of specific, well defined strata, but concepts derived secondarily from the strata and from other field evidence. Furthermore, most of the field entities on which the chart is based are not supported by published definitions or descriptions precise enough to permit reproducibility, that is, clear identification in the field by persons other than the original proposer.

Compared with the systems in use elsewhere, the climatic scheme has these disadvantages:—

(1) Its units are not objective and not reproducible. Strata, having bases and tops, afford less room for differences of opinion than do climatic concepts, which are second-order derivations.

(2) By differing fundamentally from more conventional systems it puts obstacles in the way of inter-regional correlation.

(3) Its use tends to give the false impression to those at a distance from East Africa that its component parts actually are stratigraphic entities. This leads to misunderstanding and confusion.[1]

(4) As change of climate may not have been synchronous throughout a wide region (Cooke, 1955), correlation by climate may lead to errors.

In defence of the climatic scheme, it might be argued that as sheets of glacial drift possess climatic implications, the Pleistocene glacial-stratigraphic system constitutes a precedent. The argument, however, is not valid, because it is not the climatic implications, but the drift sheets themselves (e.g. Saale drift, Gipping till) that constitute the units, which are therefore objective physical entities.

It might be argued also that faunas, particularly terrestrial faunas

[1] As Mrs. Cole (1954, p. 44) remarked, " names given to the pluvials have assumed a stratigraphical significance over the whole continent." Hopwood (in Leakey, 1951, p. 20) deplored the application of the names of pluvials to faunal zones. Cooke (1955) commented on their use in a stratigraphic sense.

such as constitute the bulk of the known Pleistocene faunas of East Africa, are closely related to climate through ecologic controls, and that, therefore, climate finds a natural place in the conventional scheme of stratigraphic classification. But the fossil mammals identified thus far possess few if any climatic implications. The Pleistocene fossil faunas differ little from the existing fauna in an ecologic sense (H. B. S. Cooke, unpublished). The similarity invites the inference that Pleistocene changes of climate in East Africa were not profound enough to induce much change (as distinct from evolutionary changes of other kinds) in the faunas hitherto found as fossils.

For these reasons, I conclude that climate as a primary basis of any stratigraphic scheme is undesirable. This conclusion, as should be evident from the discussion in the first half of this paper, does not constitute an attack on the reality of Pleistocene climatic change in East Africa, for such change seems truly to have occurred. It seeks only to re-establish climate in the secondary position in which it properly belongs in any stratigraphic scheme.

Pleistocene Correlation in East Africa

If the climatic scheme should be abandoned in favour of a more conventional scheme, what is the status in East Africa of the elements necessary for the latter scheme? These elements are (1) rock units with physical characteristics, (2) faunal zones, and (3) cultural material. Each must be briefly considered.

(1) Rock units, carrying geographical names from localities where sequences of strata are exposed, have been described from many localities. An example is the Laetolil beds in Tanganyika (Kent, 1941, p. 178). Such units, described in physical terms, constitute the basic materials for erecting a conventional scheme of correlation. Physical features which the literature shows have been useful for correlation include grain size in alluvium, sorting, rounding, and surface character of sand grains in eolian sediments, ancient soils and weathering zones, and stratification in lake-floor sediments. On such bases sediments of stream, lake, and eolian origin have been separately identified. Individual sequences, however, are difficult to correlate because, like most terrestrial strata, the majority of the sedimentary bodies were never continuous but were deposited in separate basins. The nearest approach to an exception consists of long, narrow, and mostly thin bodies of alluvium in the valleys of major streams, but even these have become discontinuous by dissection.

(2) Faunal zones, carrying geographical names from localities of their occurrence, have been proposed. Examples are Kaiso, Olduvai, and Gamble's Caves faunal zones (Hopwood in Leakey, 1951, p. 20).

Correlation of Pleistocene fossil-bearing strata in East Africa by conventional methods is as practicable as in other regions where terrestrial vertebrates predominate. The faunal chart prepared by Cooke (1958, p. 56) represents existing knowledge in an objective and realistic way.

(3) Cultural material assumes a peculiar importance in this region. No one who has not actually seen them can fully appreciate how enormous is the number of stone implements in Africa, interbedded in Pleistocene sediments and lying on the present surface. Where several cultures are found in vertical sequence at a single locality, they are consistent internally; that is, degree of cultural evolution increases upward. In general, also, marked cultural evolution is evident within upper parts of the Pleistocene sequence, in which no conspicuous change in the fossil mammals has been discerned. For these three positive reasons, as well as for the negative reason that information on Pleistocene fossil mammals is still scanty, distinctive assemblages of stone implements have been used to a greater extent than on other continents, as a means of stratigraphic correlation.

The validity of the use of assemblages of artifacts as one would use assemblages of fossils rests on three bases. (1) Abundance of occurrence of the material; that is, both abundance of individual objects at a locality and comparatively close spacing of localities. (2) Employment, as indices, not of single artifacts but of full ranges of implements and flakes. This implies the making of extensive collections and their thorough study, including statistical treatment, like that given to an abundant fossil fauna. (3) The assumption that a given cultural phase was essentially contemporaneous throughout a wide region. This is not yet established, but seems probable for social groups that lived by hunting rather than by the more sedentary practice of agriculture.[1] The argument that a wide range of material cultures, from Neolithic to electronic, exists to-day is not a valid argument that Palaeolithic hunting cultures were similarly steeply time transgressive. To-day's cultural discrepancy has developed within a comparatively very short time in response to industrial forces that did not exist in Palaeolithic time. Palaeolithic innovations in technical skill seem to have spread rapidly, for such innovations appear at the same general stage of cultural evolution at widely separated localities. Furthermore, the few results of C^{14} dating of culture horizons in Africa are generally compatible with the concept of contemporaneous cultural evolution over considerable areas.

Of the three bases of validity of cultural materials as index " fossils ",

[1] Dr. J. D. Clark (unpublished) gave me a reasoned argument in support of the concept of contemporaneity within broad limits, which it is hoped will be published within the near future.

(1) is rather commonly a fact, (2) is a matter of improved technique employed increasingly, and (3) remains, for the present, a reasonable assumption. We can expect that wide acceptance of correlation by cultures will follow the accumulation of internal evidence of agreement among cultural sequences over wide areas, and the application of external checks from improved knowledge of physical stratigraphy and from C^{14} dating. Meanwhile such correlation is in wide use in Africa for the practical reason that on much of the continent it is the only means of correlation presently available, apart from the broad and unrefined means afforded by fossil mammals.

What has been written above applies to cultures to the origin of which no doubt attaches. The "Kafuan culture" [1] cannot be employed usefully in correlation until general agreement has been reached that the "Kafuan" objects are indeed mainly artifacts. At present, agreement on this point is not general. The objects have been classed as pebble tools, and whereas some of those of "more evolved" character may well be genuine, there is room for doubt as to whether the "less evolved" majority are so. Their occurrence alone affords no support for their interpretation as artifacts, as it is confined to natural deposits; the objects are pebbles in pebble gravels laid down by rivers such as the Kafu and Kagera in Uganda.

The three entities discussed—rock units, faunal zones, and cultural materials—constitute, as a group, a reasonable basis from which can emerge broad correlation that will inspire confidence, and it is suggested that this basis be adopted for East Africa. Correlation charts are essentially reports of progress and as such invite improvement from year to year. Their rather transitory nature should not, however, relieve their authors of the responsibility of distinguishing among the classes of data from which they are constructed, and to make as clear as possible which data are primary and which are dependent. A good chart, therefore, should show rock units, faunal zones, and cultural phases in separate columns and, if inferred climates likewise are shown, being based on dependent data they should be in a column of their own. Examples of such separation are Tables 2 and 3 in Cole, 1954. In those tables, however, the columns listing "geological stages" fail to define the meaning of the subdivisions Lower, Middle, and Upper Pleistocene. It should be general practice either to define such terms or to state which of two or more published definitions is being adhered to; otherwise the correlation of local entities with them is either ambiguous or meaningless. In Cole's tables, we do not know whether the three Pleistocene subdivisions are used in the sense of groups of glacial and interglacial units occurring in Europe (for example Zeuner, 1935, p. 372), in a faunal or quasi-faunal sense

[1] Described in Lowe, 1952.

(Hopwood, 1935, p. 56–57), or on a mixed basis, with Upper Pleistocene defined in terms of climate and Middle and Lower Pleistocene in terms of cultural content (Leakey, 1935, p. 4). It is doubtful whether these three subdivisions should be used at all. In the present state of knowledge the only valid basis for their use in East Africa is a faunal one, for the terms are European and faunas are at present the only common denominator pertinent to the two regions.

Other entities that should become useful with growth of knowledge are floral zones, such as are in use by pollen stratigraphers in Europe and in North America, and C^{14} dates, uniquely useful for time correlation within the uppermost part of the stratigraphic column, the part representing the last 70,000 years or so.

On the combined basis of all these entities, stratigraphic correlation in East Africa could proceed on a conventional basis similar to those employed in the rest of the world. A locality admirably adapted as a starting point is the Olduvai Gorge, where distinctive rock units, fossils, and cultures exist in magnificent exposures. Systematic development of these entities in the Olduvai Gorge succession should make possible the establishment of a solid scheme to which entities elsewhere could be correlated.

Acknowledgments

During the course of my tour, I had the good fortune to visit, in company with geologists or prehistorians familiar with the local sequences, a large number of localities in the Belgian Congo, Uganda, Kenya, and Tanganyika, including these:

In the Western Rift Valley: Rwindi; Ishango and other localities in the Semliki Valley; Kaiso.

In the Lake Victoria basin: Nsongezi and other sites in the Kagera Valley; Kanam and Kanjera.

In the Eastern Rift Valley region: Gamble's Cave, Nderit Drift, Melawa Gorge, Little Gilgil River, Kariandusi, Njorowa Gorge, Lion Hill Cave, Naivasha Railway Rock Shelter; Wetherall's, Durie's, and Cartwright's Sites on the Kinangop Plateau; Olorgesailie, Magadi, Olduvai Gorge.

I gratefully acknowledge financial support from the Wenner-Gren Foundation of New York, which made possible the extensive travel on which this discussion is based. My sincere thanks are due also to those who guided or accompanied me to sites in the field and illuminated their meaning with excellent discussion: B. H. Baker, W. W. Bishop, Jean de Heinzelin, L. S. B. Leakey, Merrick Posnansky, and Philip Tobias. Although I did not have an opportunity to visit the field with him, I profited from discussion and correspondence with E. J. Wayland. My discussions with H. B. S. Cooke were invaluable.

I acknowledge also helpful criticism and comments on the manuscript, from W. W. Bishop, J. D. Clark, Sonia Cole, H. B. S. Cooke, and L. S. B. Leakey.

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Scapolite-Bearing Marbles and Calc-Silicate Rocks from Tungkillo and Milendella, South Australia

By A. J. R. White

(PLATE VI)

Abstract

On the eastern side of the Mount Lofty Ranges of South Australia, impure marbles and calc-silicate rocks characterized by assemblages rich in scapolite and pyroxene have been formed on a regional scale by high grade metamorphism of limestones and calcareous shales. It is suggested that this metamorphism is essentially isochemical and that even chlorine in the scapolite (Me 55–60) could have been derived from the original sediments.

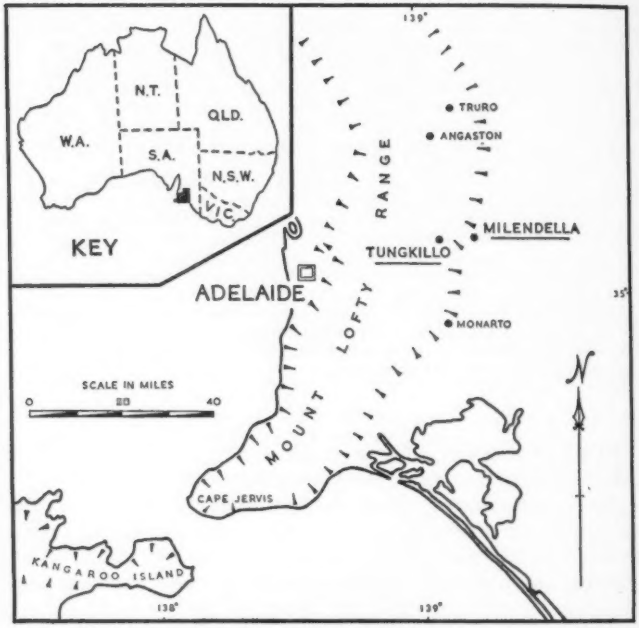
A secondary paragenesis consisting of epidote, actinolite, and calcite at Tungkillo and epidote, actinolite, calcite, and garnet at Milendella, is the result of late metasomatism and reaction associated with the formation of granites, migmatites, and veined gneisses. At Tungkillo, outside the sphere of granite activity, the secondary, retrograde assemblage is due to limited metasomatism chiefly involving the introduction of water, whereas at Milendella where marbles and calc-silicate rocks are intimately associated with granitic rocks, reaction and metasomatism giving rise to the secondary minerals has been more intense. Here garnet of the andradite-grossularite series has developed.

Introduction

THIS paper is a contribution to the problem of the petrogenesis of regionally developed scapolite-bearing assemblages.

On the eastern side of the Mount Lofty Ranges of South Australia, calcareous rocks including marbles, occur near the base of a great thickness of metamorphosed greywackes and siltstones which have been variously ascribed to the Barossian System of older Precambrian age (Woolnough, 1908), the Adelaide System of later Precambrian age (Howchin, 1929), and the Kanmantoo Group of Cambro-Ordovician age (Sprigg and Campana, 1953). Recent structural work by Kleeman and Skinner (1959) suggests that the metagreywackes in the vicinity of Tungkillo and Milendella, about 35 miles due east of Adelaide, belong to a geosynclinal facies of the upper part of the Adelaide System although they pass conformably up into the Kanmantoo Group. The rocks of this geosyncline including the calcareous rocks described here, were folded and metamorphosed on a regional scale during an early Palaeozoic orogeny producing the rocks of biotite grade and higher that are now exposed along an arcuate belt, over 200 miles long, extending from Kangaroo Island through Cape Jervis and Monarto to Truro in the north (Text-fig. 1). In an area of several hundred square miles between Monarto and Angaston, the rocks belong to the amphibolite facies of metamorphism and near the centre of this belt, meta-

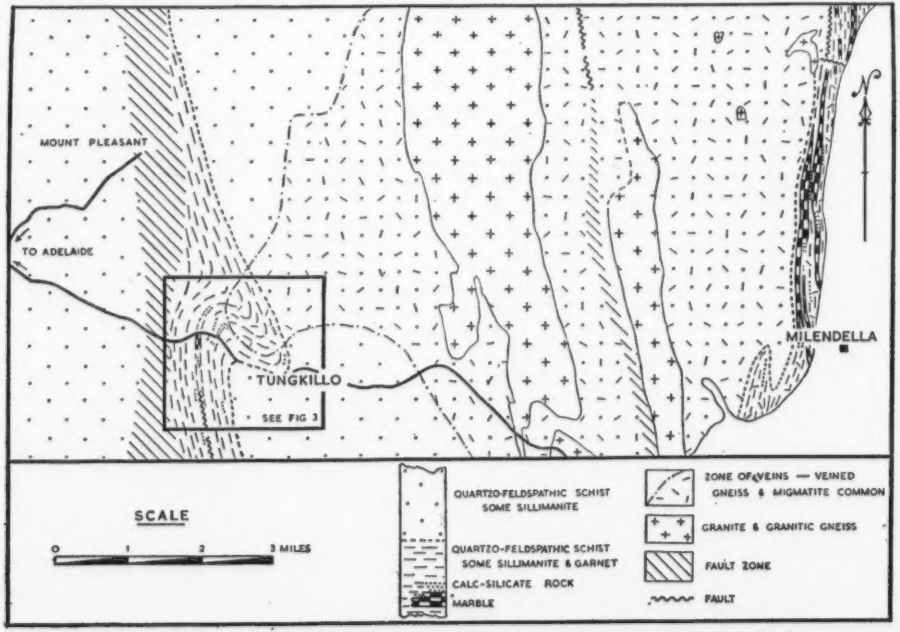
morphism culminates in the widespread development of veined gneiss and migmatite which form an envelope, referred to here as the zone of veins (cf. Read, 1931, p. 91) around masses of granitic gneiss and granite. In this paper scapolite-bearing marbles and calc-silicate rocks from Tungkillo, situated outside the zone of veins are compared with



TEXT-FIG. 1.—Locality Map.

similar rocks from within the zone in the hills west of Milendella (Text-fig. 2).

The calcareous rocks from these two localities are characterized by an abundance of scapolite, as indeed are most of the calc-silicate rocks of the Eastern Mount Lofty Ranges. In fact scapolite-bearing rocks are so abundant throughout many hundreds of square miles that the area may be regarded as a regional scapolite province comparable in some respects to the scapolite provinces of the Cloncurry district of north-west Queensland (Edwards and Baker, 1954) and the Kiruna district of Sweden (Sundius, 1915) although in the occurrences described here, the scapolite is a calcium-rich variety and is not considered to be a product of regional pneumatolytic metasomatism.



TEXT-FIG. 2.—Simplified geological sketch-map of the Tungkillo–Milendella district.

The Tungkillo Occurrences

Field relationships and associated rocks.

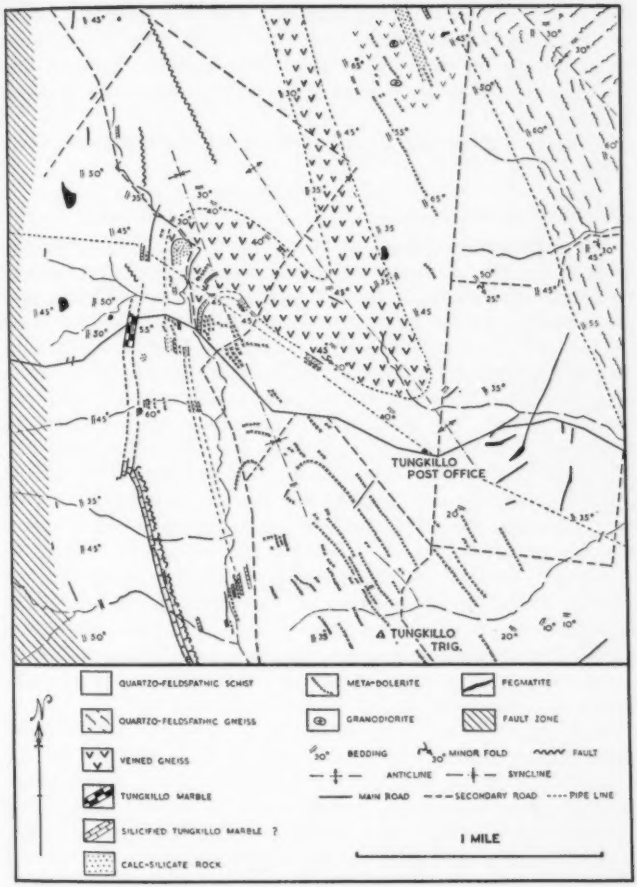
At Tungkillo, calc-silicate rocks and a marble are interbedded with quartzo-feldspathic schists in which bedding is clearly defined by alternations up to 1 cm. thick, of more micaceous laminae and laminae rich in quartz and feldspar. These host schists consist essentially of quartz, plagioclase (usually oligoclase), potash feldspar, biotite, and muscovite; almandine and tufts of fibrolitic sillimanite replacing the micas are present in several of the specimens examined. Quartzo-feldspathic veins almost invariably parallel to the bedding are common north of the village and amphibolites representing pre-metamorphic basic sills and dykes are abundant in rocks immediately above the calcareous horizon.

The calc-silicate rocks usually outcrop as tabular projecting sheets whose shape is determined by the original bedding. However, individual beds of these rocks and of the marble cannot be traced in the field for more than a hundred yards or so, and although exposures are isolated, it seems that the beds are lenticular and thin out, or grade into quartzo-feldspathic schists. The marble is seen only in a small quarry on the Tungkillo-Adelaide road, but southwards along the projected strike of the roadside occurrence a quartzite or silicified rock associated with powdery white earthy material is taken as the continuation of the bed. North of the quarry it is thought to pass rapidly along the strike into calc-silicate rock.

Taken as a group the calcareous rocks are traceable for some four to five miles and are folded into a south-easterly plunging syncline and anticline (Text-fig. 3).

The Tungkillo Marble.

The marble is a coarse-grained, white rock in which bedding is frequently preserved by the planar arrangement of accessory minerals which form tiny projections on the weathered surface. Large lenticular porphyroblasts of calcite up to 5 mm. across and aligned with their two longest axes in a plane of foliation dipping eastwards at about 50°, are set in a fine-grained matrix of small sutured interlocking grains. The texture is reminiscent of mortar structure and indeed the large prophyroblasts all show bent twin lamellae. The other component minerals, quartz, potash feldspar, pyroxene, tremolite, phlogopite, scapolite, sphene, and pyrite, are present in variable amounts but seldom total as much as 4 per cent of the rock. Phlogopite (α = colourless, $\beta = \gamma$ = pale brown) and scapolite are rare or irregularly distributed. Quartz and to a lesser extent feldspar appear as zenoblastic grains showing rounded outlines against the enclosing calcite. The pyroxene



TEXT-FIG. 3.—Geological Map of the Tungkillo Area.

($2V_y = 60° \pm 2°$) is colourless or very faintly green, indicating a composition near pure diopside. Ragged diopside individuals are often surrounded and obviously replaced by single crystals of colourless tremolitic amphibole ($2V_\alpha = 84° \pm 3°$); in prismatic sections the cleavage traces of both minerals and therefore the *z* crystallographic axes are parallel, whereas in basal sections, lines bisecting the angle between the (110) and ($\bar{1}10$) cleavage traces of both and hence

the *y* axes are more or less parallel. This is a good example of epitaxic replacement (cf. Kostov, 1957). Tiny particles of calcite and quartz within the tremolite or at diopside-tremolite junctions were probably formed as by-products of the transformation of diopside to tremolite.

An analysis of the marble quoted from Jack (1923) is given in Table I, Column 1.

Pyroxene-scapolite rocks.[1]

The characteristic calc-silicate assemblage at Tungkillo is pyroxene-scapolite-sphene. A simple example is that of a dark greenish-grey rock (15747)[2] collected from the top of a conical hill, three hundred yards south of the marble quarry. Its colour, even grain-size (average 0·25 mm.) and lack of sedimentary banding give it the outward appearance of a fine-grained igneous rock although it consists almost entirely of a granoblastic aggregate of pyroxene and scapolite approximately in the ratio of 4:3; tiny granules of brown sphene are an ever-present accessory. The pyroxene is bright green and faintly pleochroic with $2V_\gamma = 60° \pm 1°$, $\gamma \wedge c = 45°$ and the β refractive index 1·723. According to Hess's (1949) curves, these properties correspond to a pyroxene near 20 per cent diopside and 80 per cent hedenbergite. The scapolite has the refractive indices, $\omega = 1{\cdot}576$ and $\epsilon = 1{\cdot}550$, thus corresponding to about 60 per cent meionite according to Tröger's curves (Tröger, 1952). Small amounts of dark bluish-green hornblende (α = yellow-green, β = dark grass green, γ = dark blue-green) surround and obviously replace the pyroxene. Tiny particles of quartz recognizable along the pyroxene-hornblende junctions, provide additional evidence that the hornblende was formed from the pyroxene (Plate VI, fig. 1). A few grains of epidote are likewise in disequilibrium with scapolite which becomes quite cloudy near the irregular epidote boundaries. The analysis (Table I, Column 2) shows the high lime and high ferrous iron content expected from the mineral composition, while the low percentage of chlorine and absence of sulphur reflect the dominance of carbonate meionite in the scapolite.

Quartz or microcline or both in widely varying amounts, accompany scapolite, pyroxene, and sphene in the majority of the Tungkillo calc-silicate rocks whether these are banded, massive, coarse grained or fine grained. The following are typical assemblages. In all examples those minerals which appear to be out of equilibrium with the main assemblage are listed as secondary.

[1] Because of the granulose texture found in such rocks, many authors use the name " pyroxene-scapolite-granulite " but it seems preferable to refer to them simply as " pyroxene-scapolite rocks ".

[2] Numbers refer to the rock catalogue at the University of Adelaide.

TABLE I

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	2·30	47·76	41·61	40·48	34·08	40·14	40·08	37·79	37·48	42·13	31·66
Al_2O_3	1·31	11·36	8·09	9·63	6·63	1·85	5·36	3·37	5·78	12·98	9·21
TiO_2	0·03	0·76	0·12	0·64	0·10	Tr	0·18	Tr	0·49	0·86	—
Fe_2O_3	0·11	1·24	12·12	1·05	9·93	1·09	2·17	2·86	1·31	3·36	4·52
FeO	0·49	10·81	8·53	9·16	6·99	5·57	4·96	5·66	2·21	2·79	—
MnO	0·16	0·42	0·29	0·36	0·24	0·53	0·56	0·59	0·32	0·33	—
MgO	0·73	3·40	2·54	2·88	2·08	8·85	7·97	8·65	9·31	3·07	2·07
CaO	52·14	20·01	24·71	16·96	20·24	16·36	13·68	16·05	18·36	15·89	25·68
Na_2O	0·09	1·48	0·50	1·25	0·41	0·90	1·12	0·78	0·52	0·70	1·63
K_2O	0·23	0·33	0·28	0·28	0·23	0·80	0·99	0·59	0·85	2·80	1·33
P_2O_5	0·12	0·09	0·22	0·08	0·18	0·04	0·06	0·04	0·12	0·07	—
H_2O^+	0·10	0·28	0·19	0·24	0·16	2·49	3·00	1·60	1·25	1·70	6·02
H_2O^-	0·15	0·18	0·23	0·15	0·19	0·01	0·03	0·06	0·05	0·53	—
CO_2	42·00	1·35	0·06	16·45	18·15	21·28	19·86	21·67	20·47	12·37	17·13
SO_3	0·07	Nil	0·05	—	0·04	0·23	0·20	0·45	1·50	—	0·27
Cl	0·01	0·44	0·47	0·37	0·38	Tr	Tr	0·01	—	—	2·46
	100·04	99·91	100·01			100·14	100·22	100·17	100·02	100·00[1]	101·98
— O for Cl	—	0·10	0·10			—	—	—			0·54
Total	100·04	99·81	99·91			100·14	100·22	100·17	100·02		101·44

EXPLANATION OF TABLE I

1 includes 0·38 per cent S and 0·04 per cent C.

Analyses of Rungkillo and Milendella rocks and some calcareous shales with percentages of lime comparable with those of the calc-silicate rocks.

1. Tungkillo marble. Analyst : W. S. Chapman in Jack (1923).
2. Pyroxene-scapolite rock. Tungkillo, South Australia. Analyst : A. J. R. White.
3. Garnet Skarn. Milendella, South Australia. Analyst : A. J. R. White.
4. Analysis 2 recalculated to 100 per cent assuming all Ca and Mg were originally present as carbonates.
5. Analysis 3 recalculated to 100 per cent assuming all Ca and Mg were originally present as carbonates.
6. Carbonate shale. Black Star mine, Mount Isa, Queensland. Analyst G. C. Carlos in Edwards, Baker and Callow (1956).
7. Carbonate shale. Black Star mine, Mount Isa, Queensland. Analyst : G. C. Carlos in Edwards, Baker and Callow (1956).
8. Carbonate shale. Black Star mine, Mount Isa, Queensland. Analyst : G. C. Carlos in Edwards, Baker and Callow (1956).
9. Carbonate shale. Footwall rock, Dugald River, lead-zinc prospect, Queensland. Analyst : G. C. Carlos in Edwards, Baker and Callow (1956).
10. Calcareous Shale, Sandvika, Oslo Region. Analysis quoted by Hagemann (1957) after Kvalheim.
11. Red coastal mud (marl) Brazil. Quoted from Niggli 1952, page 310).

15753. Pyroxene ($\beta = 1{\cdot}703$), scapolite ($\omega = 1{\cdot}577$), quartz, microcline, sphene, apatite.

Secondary: Hornblende, epidote.

15748. Pyroxene ($\beta = 1{\cdot}705$), scapolite ($\omega = 1{\cdot}576$), quartz, microline, sphene, apatite.

Secondary : Hornblende, epidote.

15749. Pyroxene (Salite, see analysis), scapolite ($\omega = 1{\cdot}576$, $\epsilon = 1{\cdot}554$), microline, sphene, apatite.

Secondary : Hornblende, calcite, epidote, quartz.

15752. Pyroxene ($2V_\gamma = 60° \pm 1°, \beta = 1{\cdot}683$), scapolite ($\omega = 1{\cdot}577$, $\epsilon = 1{\cdot}552$), quartz, sphene.

Secondary: Epidote, calcite, actinolite (α = colourless, β = pale green, γ = pale green, $\alpha < \beta < \gamma$, $2V_\alpha = 82° \pm 2°$, $\gamma \wedge c = 13° \pm 2°$).

Hornblende-scapolite rocks.

Hornblende, when present as an essential constituent, either accompanying pyroxene or as hornblende-rich bands within pyroxene-scapolite rocks, appears to be in equilibrium with scapolite and is therefore regarded as primary. A few flakes of brown biotite are present in occasional rocks lacking pyroxene. The following are typical assemblages:—

15754. Hornblende, scapolite ($\omega = 1{\cdot}576$), quartz, microcline, biotite, sphene, tourmaline, magnetite.

Secondary: Epidote, calcite.

15756. Hornblende, quartz, microcline, scapolite.

Secondary: Epidote ($2V_\alpha = 81°$).

Scapolite-pyroxene rocks containing plagioclase.

Only two scapolite-bearing rocks were found to contain plagioclase. One (15755) consists of fine regular alterations of hornblende-rich bands and bright green pyroxene-rich bands; the other is coarse grained (average 0·4 mm.) and irregularly banded. Because of the absence of textural evidence to suggest the contrary even when scapolite and plagioclase are in contact, it is assumed that both minerals are in equilibrium. The two assemblages are:—

15755. Hornblende, pyroxene ($\beta = 1{\cdot}697$), microcline, quartz, plagioclase (An 60), scapolite ($\omega = 1{\cdot}576$), biotite (in hornblende bands only), sphene, apatite.

15749. Pyroxene ($\beta = 1{\cdot}704$), scapolite ($\omega = 1{\cdot}576$), plagioclase (An 50), quartz, sphene, apatite, pyrite.

Secondary: Epidote, calcite, sericite, magnetite.

Calc-silicate rocks without scapolite.

Calc-silicate rocks without scapolite but otherwise similar in appearance and mineral composition to those described above, are relatively rare at Tungkillo. Two assemblages are:—

15751. Pyroxene ($\beta = 1{\cdot}706$), microcline, quartz, sphene, apatite.

Secondary: Epidote, actinolite.

15757. Hornblende bands: Hornblende (α = yellow green, β = olive green, γ = dark green), plagioclase (An 45), quartz, microcline, sphene, apatite. Pyroxene bands: Pyroxene ($\beta = 1{\cdot}698$), quartz, plagioclase (An 40), hornblende, sphene, apatite.

Several other rocks without scapolite, exemplified by two specimens (15758 and 15759) collected from a vein on the roadside one hundred yards south of the marble quarry, consist essentially of epidote and patchy green actinolite (general pleochroic formula: α = colourless, β = pale green, γ = bluish green) and minor quartz and sphene These are considered to be secondary assemblages.

The Milendella Area

Field relationships and associated rocks.

Extensive outcrops of marble and associated calc-silicate rocks occur in the hills that rise steeply from the alluvial Murray Plains about ½ mile west of Milendella village (Text-fig. 2). From here they extend in a northerly direction to the edge of the Mannum Sheet (White and Thatcher, 1957). In contrast to the Tungkillo occurrences this calcareous horizon is wholly within the zone of veins and in the south it is associated with a migmatite complex consisting of an intimate mixture of veined gneiss, quartzo-feldspathic schist (sometimes with sillimanite), aplitic granite, and pegmatite. Within the horizon are two main beds of marble each up to 400 feet thick and both dipping westwards between 45° and 60°, as well as smaller lenticular marble beds. The calc-silicate rocks occur as individual beds within the quartzo-feldspathic schists and gneisses, as pods and bands within the marbles, or as marginal variants of the marbles.

The Milendella Marbles.

These are similar in most respects to the Tungkillo marble, although they are generally finer in grain and contain more impurities (usually about 10 per cent). These include pyroxene varying from almost colourless to bright green, scapolite, potash feldspar, and sphene. Sometimes epidote replaces scapolite and occasionally amphibole replaces pyroxene. A typical marble (15761) consists of the following minerals all of which appear to be in equilibrium:—

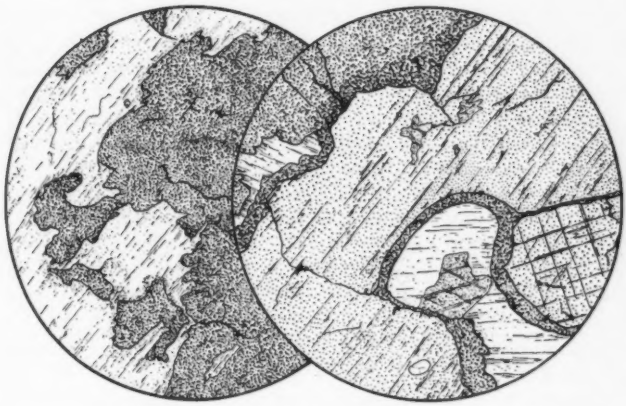
Calcite 90 per cent; both large and small grains are present. Potash feldspar 5 per cent; twinning is completely absent but stain tests prove that all the feldspar is a potash variety. The optic axial angle is variable with some values as low as $45° \pm 2°$ and the refractive index (β) is 1·523. Pyroxene 3 per cent; the rounded grains of pyroxene are dark green with $\beta = 1{\cdot}702$, $2V_\gamma = 60° \pm 1°$ indicating a composition near 60 per cent Di 40 per cent He (Hess, 1949). Scapolite 2 per cent. Accessories include apatite, pyrite, and sphene.

Like the Tungkillo marble, many specimens show pronounced deformation phenomena such as mortar or cataclastic structures. One example (15762) that appears very fine grained in hand specimen, is seen under the microscope to consist of lenticular calcite augen in a matrix of very fine grained granules. In this mylonitized rock, the almost colourless pyroxene frequently shows lamellar twinning parallel to (100), a phenomena not common in pyroxenes of the other rocks and therefore possibly caused by the movement.

Calc-silicate rocks.

Although many of the calc-silicate rocks from the Milendella belt are almost identical to the massive or banded Tungkillo types and some contain the typical Tungkillo assemblage pyroxene-scapolite-microcline-quartz-sphene, the most conspicuous are reddish-brown garnet skarns. The best example of such a skarn is found in the migmatite complex about one mile south-east of Milendella where a bed of red-brown garnet rock about 20 feet wide, extends in a north–south direction for $\frac{3}{4}$ mile. Some of the specimens from this locality consist predominantly of red-brown garnet throughout which are scattered large scapolite individuals with cloudy and embayed margins; others consist of crude alternating bands, two or three millimetres in width and made up essentially of scapolite and garnet, pyroxene and garnet or almost entirely of garnet. In one of these banded rocks the garnet has $N = 1{\cdot}847$, S.G. = 3·86, $a = 11{\cdot}954$ ($\pm$ ·003 Å), and MnO = 0·43 per cent, indicative of an andradite with a relatively high percentage of grossularite and almandine. Most of the pyroxene is a pale green variety ($\beta = 1{\cdot}713$, $2V_\gamma = 61° \pm 1°$) that is partly altered particularly along the cleavages to blue-green amphibole or sometimes pale green epidote, but some bands contain a quite unaltered and distinctly brighter green pyroxene (α = bright green with a slight bluish tint, β = bright green, γ = paler green with a slight yellow tint, $2V_\gamma = 63°$, $\beta = 1{\cdot}720$). Scapolite has refractive indices slightly lower than those recorded from Tungkillo ($\omega = 1{\cdot}575$, $\epsilon = 1{\cdot}550$). Some epidote and calcite are obviously secondary. Except for the abundance of garnet, the skarn is similar to the banded scapolite-pyroxene rocks of Tungkillo. The most striking difference in the

analysis is the higher ferric iron content (Table I, Column 3) reflecting the high andradite content of the garnet. The small amount of sodium is indicative of a meionite-rich scapolite in spite of the lower refractive indices and the fact that the chlorine content is comparable with that of the Tungkillo rock. In the analysed rock many scapolites have cloudy and embayed margins when in contact with garnet and where garnet is very abundant the bulk of the pyroxene is partly altered to



TEXT-FIG. 4.—(*a*) Portion of a scapolite crystal partly replaced by garnet. 15771. × 95.
(*b*) Rims of garnet between scapolite and pyroxene. Note the dark colour of the garnet where it is in contact with the pyroxene. Calcite and quartz are present in minor amounts. 15771. × 95.

hornblende; thus there is some evidence that garnet belongs to the secondary paragenesis. This relationship is clearer in a coarse-grained garnet skarn collected from a pod, 6 feet by 3 feet, within the marble 1½ miles NNW. of Milendella. This skarn is again dominated by garnet in coarse segregations up to several inches across between which are patches of dark green pyroxene, greasy white scapolite, and pale green epidote. Calcite, quartz, sphene, and pyrite are present in minor amounts. Most of the garnet is a pale red-brown grossularite containing a high percentage of almandine (Analysis 1, Table III). Where in contact with garnet, scapolite again has irregular, cloudy, and embayed margins, particularly when it occurs as skeletal, obviously relict cores completely enclosed by garnet. (Text-fig. 4A.) Often the garnet forms regular rims around a scapolite individual comparable in every detail with those described from similar rocks by Drever (1939). It is

notable that anywhere in this rock where garnet is abundant, scapolite and pyroxene are never in contact but are always separated by a rim of garnet that is slightly darker in colour than the grossularite (Text-fig. 4B) suggesting the possibility that garnet has been partly derived

TABLE II

	1 Pyroxene		2 Scapolite	
	Wt. %	Atomic ratios to 6 oxygens	Wt. %	Semi-empirical unit cell contents
SiO_2	50·73	1·945 } 2·00 Z	51·10	15·64 } 24·69
Al_2O_3	1·97	·055 }	25·10	9·05 }
		·034		
TiO_2	0·10	·003	0·05	·01
Fe_2O_3	1·47	·044	0·33	·08
FeO	12·98	·416 } 1·03 X, Y	0·12	·03
MnO	0·53	·017	0·01	·00 } 7·82
MgO	9·07	·518	Nil	—
CaO	23·00	·944	12·54	4·11
Na_2O	0·25	·019 } 0·97 W	5·38	3·19
K_2O	0·12	·006	1·03	·40
CO_2	n.d.		2·88	1·20
SO_3	n.d.	$Ca_{49}Mg_{27}Fe_{24}$	0·11	·03 } 1·96
Cl	n.d.	% Al in Z = 2·8	1·42	·74
H_2O^+	n.d.		0·49	
H_2O^-	0·15		0·13	0 = 53·42
	100·37		100·69	
Less O for Cl.	—		·31	
Total	100·37		100·38	
Colour				
Hand specimen	Dark green		Greasy white	
Thin section	Green		Colourless	
Refractive indices	$\alpha = 1·698 \pm ·001$		$\omega = 1·574 \pm ·001$	
	$\beta = 1·703$,, ,,		$\epsilon = 1·549$,, ,,	
	$\gamma = 1·727$,, ,,			
Optic axial angle (2V)	$59° \pm 1°$		—	
Specific gravity	$3·43 \pm ·01$		$2·68 \pm ·01$	

from the pyroxene. Quite apart from the grossularite and the associated darker garnet rims, some segregations consist of another garnet which is quite black in hand specimen but pale coffee coloured in sections; it is an andradite, again having a high percentage of ferrous iron (Analysis 2, Table III). All three garnets have been found in one thin section (see discussion of mineralogy).

More indirect evidence for the secondary origin of garnet is obtained from the association of garnet with epidote or actinolitic amphibole or both, in some rocks without pyroxene or scapolite. Since epidote and actinolite are always secondary, such assemblages as garnet-epidote-actinolite-quartz-perthitic feldspar-ilmenite (15768) are considered to be secondary assemblages.

Some Mineralogical Details

Pyroxene, although usually one of the most abundant constituents of most marbles and calc-silicate rocks both at Tungkillo and Milendella, appears to show no systematic variation from one assemblage to another or from one environment to another. In hand specimen the colour varies from very pale green through bright green to almost black and in thin section from colourless to bright green. Apart from the {010} cleavage which is invariably well developed many crystals show (010) and (100) partings that are as regular as true cleavages. The corrected values of $2V_\gamma$ show a remarkable constancy ($59° \pm 1°$ to $61° \pm 1°$) the only departure being a value of $63° \pm 1°$ measured on the unaltered bright green pyroxene accompanying garnet in the analysed skarn, and even in this rock the altered pale green pyroxene, considered to be the earlier of the two, has a $2V_\gamma$ of $61° \pm 1°$. The β refractive indices range from $1{\cdot}683 \pm 001$ to $1{\cdot}723 (\pm 001)$. According to the curves given by Hess (1949) these optical properties correspond to the diopside-hedenbergite series with a variation in composition from 15 per cent to 80 per cent hedenbergite. The proportion of Fe atoms in the total Ca + Mg + Fe ranges from 8 per cent to 40 per cent. To check the validity of these composition variations, an analysis (Table II, Column 1) has been made of a dark green pyroxene separated from a pyroxene-scapolite-microcline rock (15749) that outcrops 600 yards north of the Mt. Pleasant–Tungkillo road junction. The mineral occurs as coarse crystals up to 30 mm. long and is relatively free from secondary alteration. By analysis Ca : Mg : Fe = 49 : 27 : 24 as compared with 50 : 27 : 23 inferred from the refractive index curves given by Hess (1949, page 641).

It is concluded that the pyroxenes occurring in equilibrium with scapolite from both Milendella and Tungkillo are simple members of the diopside-hedenbergite series with the amount of hedenbergite varying from 15 per cent to 80 per cent.

Scapolite is quantitatively next in importance to pyroxene in most of the primary assemblages. It may make up as much as 40 per cent of the total rock but sometimes it is completely absent in which case feldspar becomes an important constituent. As scapolite is never seen in disequilibrium with any mineral, including plagioclase, listed in the above assemblages as primary, it is considered to have been formed

during the main phase of regional metamorphism. The variation of refractive indices of scapolite from both Milendella and Tungkillo and from different assemblages, is small:—

$$\omega = 1{\cdot}576 \pm (\cdot001) \text{ to } 1{\cdot}574 \pm (\cdot001)$$
$$\epsilon = 1{\cdot}554 \pm (\cdot001) \text{ to } 1{\cdot}549 \pm (\cdot001)$$

The birefringence ranges from ·022 to ·026. According to Tröger's curves (Tröger, 1952) this optical data corresponds to a composition between 60 per cent and 65 per cent meionite. The scapolite from a vein-like rock (15770) [1] collected from a small pit 3 miles north of Milendella has been analysed (Table II, Column 2) after careful separation using a Cooke magnetic separator and heavy liquids. Because of doubt as to the number of anions in the unit cell, the cation contents have been calculated on a semi-empirical basis using the average cell dimensions ($a = 12{\cdot}24$ KX and $c = 7{\cdot}63$ KX) given by Pauling (1930), Goßner and Brückl (1928) and Scherillo (1935). This is considered to be legitimate since Pauling obtained the same values for meionite and for scapolite of intermediate composition and there is little variation in the values given by all three authors. On this basis the Milendella scapolite conforms fairly closely to the accepted formula. The excess of Si + Al probably means that Si is not confined to the tetrahedral positions as no free quartz was detected in the rock. The ratio of pure marialite to meionite is 43·7: 56·3. This is slightly lower than that obtained from Troger's refractive index and birefringence curves but correlation between optics and chemistry are considered to be reasonable since it is well known that K_2O and slight variations in the amount of carbonate, chlorine, and sulphate radicals affect both the birefringence and the refractive indices. The amount of these radicals in the scapolites of the region is variable as may be seen from the two analyses of scapolite-bearing rocks. In the pyroxene-scapolite rock from Tungkillo, sulphur is absent whereas the Milendella skarn and analysed scapolite both contain sulphur. Also, in the skarn containing a small amount of scapolite in comparison with the analysed pyroxene-scapolite rock, there is ·47 per cent of chlorine so that if all the chlorine is from scapolite then this mineral must contain a high percentage of chlorine meionite. The variations in CO_3^{--}, SO_4^{--} and Cl^- are probably sufficient to account for the slight variations in the optical properties.

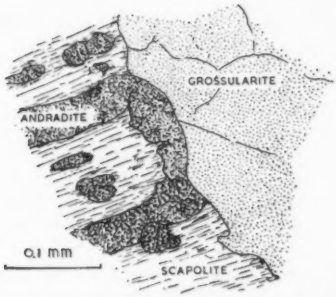
Actinolite varying from a colourless tremolitic variety to bright green depending on the orignal pyroxene of the rock, is obviously secondary whereas the *hornblende* in those scapolite-bearing rocks without pyroxene is almost certainly primary since it appears to be in equili-

[1] This specimen contains an exceptionally large amount of scapolite as crystals up to several centimetres long.

brium with scapolite. In one such rock (15754) the optical properties are indicative of an iron-rich common hornblende, a mineral whose stability in rocks of appropriate composition cannot be doubted since it is the chief constituent of the amphibolites (metadolerite sills and dykes) at Tungkillo:—

α = Greenish-yellow, β = Dark olive green, γ = Dark bluish green, $\alpha < \beta \gtrsim \gamma$. $\gamma \wedge c = 22°$ (average of 3 readings), $2V_\alpha = 76°$ (average of 3 readings), β' on (110) = 1·679.

In contrast, the hornblende (in pyroxene-scapolite rock 15753)



TEXT-FIG. 5.—Contact between grossularite and andradite.

occurring as secondary rims about pyroxene and considered to be secondary on textural evidence, has the following properties:—

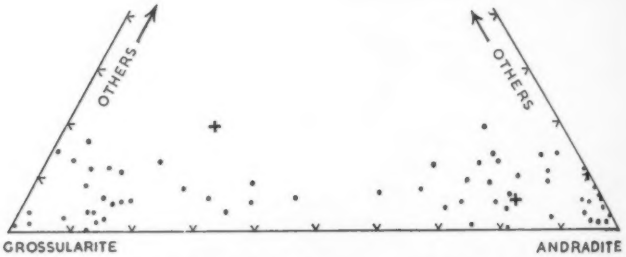
α = Greenish-yellow, β = Dark olive green with a slight bluish tint, γ = Dark greenish-blue. $\gamma \wedge c = 12°$ (average of two readings), $2V_\alpha = 53°$ (average of 2 readings), β' on (110) = 1·700.

Although the properties of this latter hornblende, particularly the optic axial angle, are less reliable because of the dark colour, small size, and small quantity, they are considered sufficiently accurate to support the hypothesis that this hornblende differs from that in the hornblende-rich rocks in both composition and origin.

Epidote is always secondary. Usually it occurs as disseminated grains replacing scapolite, pyroxene, and primary hornblende but more rarely bulbous veins appear (Plate VI, fig. 2).

On the basis of the textural evidence discussed above, *garnet* is likewise secondary. The chemistry and physical properties of two analysed garnets from Milendella, a grossularite and an andradite, are shown in Table III. They were separated from the same rock (15771) by means of a magnetic separator followed by careful hand-

picking. Both contain ferrous iron and manganese but no magnesium. The existence in the same rock of two garnet phases with contrasting Fe^{+++}: Al^{+++} ratios can be explained in two ways: either the two phases belong to the same paragenesis and could be in equilibrium, or they belong to two different parageneses both of which are secondary. However, the two types of garnet occur as separate patches and only one actual contact between them has been observed. This is sharp and lacks the embayments typical of disequilibrium relationships (Text-fig. 5). Other occurrences of two calcium garnets in the same rock have been reported but these have been explained as two genera-



TEXT-FIG. 6.—Triangular diagram showing the calculated proportions of grossularite and andradite for calcium garnets analysed since 1920. The crosses represent the compositions of two garnets occurring together in the same rock at Milendella.

tions of garnet. However, since the classic work of Boeke in 1914 (see Winchell, 1951, p. 484) mineralogists have accepted the complete isomorphism of the calcium garnet series in spite of the fact that this is in part based on old analyses many of which are inferior on present standards. Only two of 65 analyses published since 1920 (Text-fig. 6) have been found to lie within the range An 63, Gr 37 to An 45, Gr 55; one of these is an andradite (An 56·9, Gr 37·0) from an altered nepheline syenite (Milton and Davidson, 1950) and the other a grossularite (An 43·6, Gr 50·1) from South Africa (Clark, 1957). Details of the occurrence of the grossularite are not given. It is conceivable that there is a low temperature immiscibity gap in the calcium garnet series and that the Milendella andradite and grossularite belong to the same generation.

CONCLUSIONS

Origin of the primary assemblage.

The marble is clearly the result of metamorphism of a limestone containing a small amount of impurities but with the limited data

TABLE III

	1 GROSSULARITE			2 ANDRADITE		
	Wt. %	Atomic ratios to 12 oxygens		Wt. %	Atomic ratios to 12 oxygens	
SiO_2	38·51	3·026	3·03	36·65	3·042	3·04
TiO_2	0·22	·013		0·24	·015	
Al_2O_3	16·78	1·550	2·00	3·46	·338	1·93
Fe_2O_3	7·43	·439		25·23	1·574	
FeO	6·08	·399		1·59	·110	
MgO	Nil	—	2·94	Tce	—	3·02
MnO	2·20	·146		0·77	·054	
CaO	28·47	2·395		32·16	2·857	
H_2O^+	n.d.			n.d.		
H_2O^-	0·04	0 = 12·00		n.d.	0 = 12·00	
Total	99·73			100·10		
Molecular Weight (M)	470·3			498·8		
Garnet molecules (*Wt. %*) Recalculated to 100 per cent						
Grossularite	56·42			14·84		
Andradite	24·07			79·74		
Almandine	14·30			3·64		
Pyrope	—			—		
Spessartite	5·21			1·78		
	100·00			100·00		
Specific gravity Determined at 18° C	3·77 (± ·02)			3·81 (± ·02)		
Calculated from Skinner's (1956) values for end members	3·79			3·84		
Calculated from $G = \frac{1·65 \times 8M}{a^3}$	3·75			3·82		
Refractive index Measured	1·772 (± ·002)			1·846 (± ·002)		
Calculated using Skinner's values for end members	1·788			1·861		
Cell Edge (*a*) Measured	11·825 (± ·005)Å			11·986 (± ·002)Å		
Calculated using Skinner's data	11·835 Å			11·992 Å		
Colour At 100 mesh	Pinkish brown			Coffee coloured		
In thin section	Pale buff coloured			Pale brown		

available, it is impossible to determine the extent to which metasomatism has modified the original composition.

The association of calc-silicate rocks with relatively pure marble at both Tungkillo and Milendella, and the presence of uniform banding that is parallel to the bedding in the adjacent quartzo-feldspathic schists at Tungkillo, leave no doubt that these rocks are metamorphosed sediments. The analysis of a pyroxene-scapolite rock (Table I, Column 2) selected because it contains an abundance of scapolite and a high iron content as shown by the optical properties of the pyroxene, has been recalculated (Table I, Column 4) to show the composition of the original sediment assuming all lime and magnesia were present as carbonates and that metasomatism has been neglible. On this basis the chemical composition is very similar to unmetamorphosed calcareous shales containing comparable percentages of lime (Table I, Columns 6–11). As expected from the petrographic examination, the amount of ferrous iron is high but the total iron is not far above the values for some of the sediments. The ratio of sodium to potassium is also higher than in typical calcareous shales. However, as the majority of the calc-silicate rocks contain magnesium-rich pyroxenes, less scapolite and much potash feldspar, their chemistry should be even closer to some of the calcareous shales quoted from the literature. Edwards and Baker (1954) consider that the scapolite-bearing rocks of the Cloncurry region of NW. Queensland have been calcareous shales but that metasomatism involving the introduction of sodium and chlorine played a major part in their formation. In the Tungkillo-Milendella region the scapolite has a much lower sodium content (5·38 per cent compared with 10·55 per cent from Cloncurry) so that the sodium of these rocks could have been readily derived from the original sediment. Also there is no reason to suppose that chlorine which, from the data available, does not exceed 0·5 per cent and is probably only a fraction of this in many rocks, has been introduced from some extraneous source. It is not unreasonable to suppose that calcareous shales are likely to retain a small percentage of NaCl under favourable conditions of burial and lithification. If current ideas on the deposition of the overlying greywackes in this region are correct—namely that they are rapidly accumulated geosynclinal sediments that can be likened to the alpine flysch (Sprigg and Campana, 1953)—then leaching during burial would be minimized. Recent data on the halogen content of sediments, excluding evaporites, given by Behne (1953) and Lamar and Shrode (1953) show that the amount of chlorine in dolomites and limestones is higher than has hitherto been thought; Behne records a maximum of 0·2 per cent chlorine. Although no reliable data is yet available on the amount of chlorine in calcareous shales it is reasonable to assume that it would be at least as high as in

limestones and dolomites; the calcareous shales from Mt. Isa (Table I, Columns 6–8) contain at least some chlorine in spite of the fact that they have remained unmetamorphosed since Precambrian times. On the other hand the recent coastal mud from Brazil (Table I, Column 11) contains more chlorine in the analysis than is likely to be retained. It is reasonable to conclude, therefore, as Sundius did in 1915, that a high percentage of lime-rich scapolite can form in such rocks without the introduction of volatiles.

The primary assemblage of the calc-silicate rocks is thus considered to be the result of isochemical regional metamorphism of calcareous shales. The development of diopsidic pyroxene and at least some plagioclase more basic than An 30 in these rocks, together with almandine and some sillimanite in the adjacent quartzo-feldspathic schists, indicate that amphibolite facies conditions prevailed during the main metamorphism. One assemblage without scapolite (pyroxene-hornblende-plagioclase-quartz-microcline, 15757) is identical to one of the assemblages listed by Turner (1948, page 78) as being typical of the cordierite-anthophyllite subfacies.

The origin of the secondary paragenesis.

In the Tungkillo area minerals of the secondary paragenesis are mainly blue-green actinolite and epidote both of which are typical of the albite-epidote amphibolite facies. The formation of tremolite from diopside in the Tungkillo marble may be explained by the following reaction:—

$$\underset{\text{diopside}}{5\,CaMg(SiO_3)_2} + H_2O + 3\,CO_2 \rightarrow \underset{\text{tremolite}}{Ca_2Mg_5Si_8O_{22}(OH)_2} + \underset{\text{calcite}}{3\,CaCO_3} = \underset{\text{quartz}}{2\,SiO_2} \quad . \quad . \quad . \quad (1)$$

In calc-silicate rocks containing hedenbergitic pyroxene, actinolite forms in the secondary paragenesis in a similar manner. The occurrence of tiny particles of quartz and calcite within the secondary amphibole or along the ragged boundaries of partly replaced pyroxene is further evidence that such reactions have taken place.

Epidote has probably formed from meionite by hydration as in reaction (2) but there is no sign of albite or any other secondary mineral that could have formed from the marialite molecule.

$$\underset{\text{meionite}}{3(CaAl_2Si_2O_8)\,.\,CaCO_3} + H_2O \rightarrow \underset{\text{epidote}}{2\,Ca_2Al_3O_{12}\,.\,OH} + CO_2 \quad . \quad (2)$$

These secondary minerals are regarded as retrograde products. It is notable that both reactions involve the introduction of water so that this retrograde metamorphism may be regarded as a late metasomatic phase although the amount of material introduced is probably small and may even be confined to water.

The secondary paragenesis at Milendella also includes epidote and

actinolite. Reaction (3) could account for the formation of grossularite from meionite whilst some such reaction as (4) could account for the development of rims between scapolite and pyroxene together with the by-products quartz and calcite (Text-fig. 4).

$$\underset{\text{meionite}}{3(CaAl_2Si_2O_8) \cdot CaCO_3} + 5\,\underset{\text{calcite}}{CaCO_3} + 3\,\underset{\text{quartz}}{SiO_2} \rightarrow 3\,\underset{\text{grossularite}}{Ca_3Al_2Si_3O_{12}} + 6\,CO_2 \quad (3)$$

$$\underset{\text{meionite}}{3(CaAl_2Si_2O_8) \cdot CaCO_3} + 3\,\underset{\text{pyroxene}}{Ca(MgFe)Si_2O_6} \rightarrow 3\,\underset{\text{grossularite with some almandine and pyrope}}{Ca_2(MgFe)Al_2Si_3O_{12}} + \underset{\text{calcite}}{CaCO_3} + 3\,\underset{\text{quartz}}{SiO_2} \quad (4)$$

However, there are two factors which show that the formation of garnet has been more complex than this; firstly the garnets contain no magnesium and secondly the amount of ferric iron in the pyroxene (1·47 per cent in that analysed) is insufficient to account for the high percentages of the andradite molecule. Sederholm (1916) has suggested that a mineral arising within a solid rock as a reaction rim around another mineral, commonly derives some of its chemical constituents from sources outside its immediate chemical environment and Drever (1939) who described rims of garnet from remarkably similar calc-silicate rocks in the Moine series of Scotland, attributes them to metasomatism and reaction. That iron metasomatism has played a considerable part in the development of garnet at Milendella is obvious from a comparison of the analyses of the garnet skarn and the pyroxene scapolite rock which contains the most ferriferous pyroxene recorded from Tungkillo. The amount of iron in the skarn is far higher than that recorded in calcareous shales. It is concluded that the garnet is the result of reaction and metasomatism.

Thus the primary assemblage characterized by pyroxene and scapolite is the result of regional metamorphism of impure limestones and calcareous shales under amphibolite facies conditions, whilst the secondary assemblage consisting essentially of actinolite, epidote, and garnet was formed by reaction and metasomatism. The development of garnet at Milendella and not at Tungkillo is attributed to the greater intensity of metasomatism and possibly a higher temperature in this area. The association in space of garnet-bearing rocks with veined gneisses, migmatites, and granites, is evidence for the correlation of the metasomatic phase producing the secondary paragenesis with granitization.

Acknowledgments

The field expenses for this work were defrayed by a grant from the University of Adelaide for which I tender my thanks. The laboratory study was started at Adelaide, continued at Kings College, London, and completed at Otago. I am grateful to the members of the Geology Departments at these three universities for helpful criticism and advice.

Professor D. S. Coombs of Otago and Dr. A. W. Kleeman of Adelaide kindly read the manuscript.

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EXPLANATION OF PLATE VI

FIG. 1.—Hornblende forming rims about pyroxene. Note the small blebs of quartz along the junctions. 15747. × 55.

FIG. 2.—Irregular masses and veinlets of epidote (E) replacing cloudy scapolite. X-nicols. × 70.

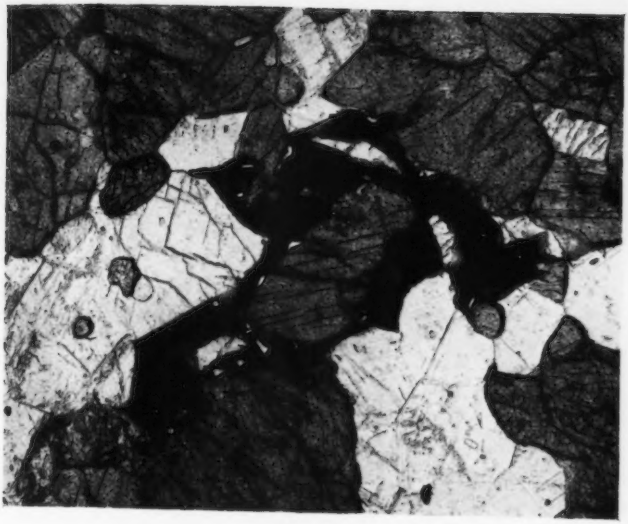

FIG. 1

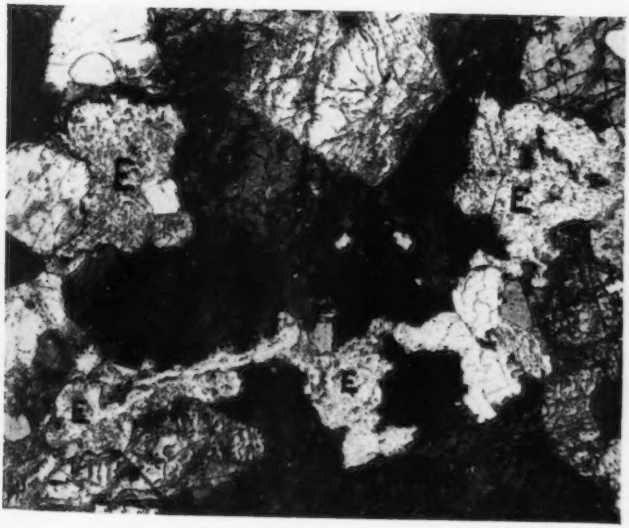

FIG. 2

SCAPOLITE-BEARING ROCKS

Concerning Mr. A. Hallam's Article on *Gryphaea*

By H. H. Swinnerton

Abstract

The basis for Mr. Hallam's rejection of the hypothesis on the evolution of *Liostrea* into *Gryphaea* is briefly examined and is shown to be inadequate. For *Liostrea* real evidence is lacking. For *Gryphaea* the evidence, though copious, is unsound for it is based upon an improper treatment of his collections. Moreover, the features he measures are not sufficiently significant and the reader is left in considerable doubt as to the actual range of his measurements. His aspersion upon previous workers in this field is entirely unjustified.

In a recent article, entitled "On the supposed evolution of *Gryphaea* in the Lias", Mr. A. Hallam (Hallam, 1959) gives us a puzzling study of this problem centring round a statistical inquiry which led him "to the rejection of Trueman's hypothesis on the evolution of *Liostrea* into Gryphaea". Such a startling judgment calls for a careful consideration of the grounds upon which it is based, especially as Trueman and those who followed him have also made extensive use of statistical methods. Unfortunately Trueman is no longer with us and cannot speak for himself. But as one who has been intimately associated with him from the outset of his career it falls to my lot to try and speak for him.

As Hallam sees it the basic picture in Trueman's work, and that of others, is "a progressive increase in coiling and reduction of the area of attachment" (p. 99). To these two morphological features he adds a third, viz., size. He says "that an increase of coiling might be entirely due to "increase of size".

In connection with this last feature it may be well to recall that gryphaeoid coiling recurs at other levels in the Jurassic rocks. If such coiling be indeed a function of size then some of the giant forms which lived later in the Jurassic should be as closely coiled as an ammonite. In actual fact they are hardly more coiled than some of the forms included by Hallam in *Liostrea irregulare*. The Gryphaeas from the *bucklandi* zone at Scunthorpe illustrate the same point. On the other hand, within the limits of my own experience, the most completely coiled specimens I have seen belong to a very small type, *G. incurva* var. *crassirugata*, which I found in the *bucklandi* zone near Granby, Nottinghamshire. This widely spread testimony from *Gryphaea* in general thus yields no support to Hallam's hypothesis concerning the relationship between size and coiling, which is an important item in his argument.

With this emphasis on size it is instructive to note how Hallam measures this feature. In measuring *Gryphaea* he takes the length of

the right valve as his index of size. He makes no mention of width or of depth, both of which are also important factors in size. Since he omits to take these into account all his discussion on size and coiling is vitiated from the outset and his fig. 4 should be labelled " length frequency " and not " size frequency ".

Besides length his other basal character is coiling, which he represents by measurements made round the periphery. This he admits " would not be satisfactory as a means of comparing *Liostrea* and *Gryphaea* " (p. 100). The cause for the unsatisfactory nature of this means for comparison, at least as far as *Liostrea* is concerned, is revealed incidentally on page 105. There we are told: (*a*) that specimens of this genus are difficult to measure accurately ; (*b*) that there is a bias in collecting specimens, and (*c*) that he has not been able to make big enough collections of complete specimens. After making this extraordinary confession we are left to infer that Hallam made no measurements on *Liostrea*. If he did make any they are not recorded in his article. There is consequently a marked hiatus in this part of his argument against Trueman. As some sort of apology for leaving this hiatus he expresses the opinion that " if it were possible to undertake a satisfactory statistical analysis the results might well suggest Trueman's story in reverse " (p. 106). He seems unaware of the fact that Trueman and others have indeed made satisfactory collections and measurements of *Liostrea* and have treated them statistically with very different results from the one Hallam has imagined. In face of all this we are quite at a loss to know what precisely is the basis of fact for the statement, in his abstract, that " No ' gryphaeoid ' trend is discernible in *Liostrea* up the Hettangian succession ". He does nevertheless recognize a " gryphaeoid " trend in these oysters (p. 105) but dismisses this as merely phenotypic, a statement for which he cannot possibly have any experimental or directly observational proof. So then the *Liostrea* section of his argument against Trueman fails completely for want of evidence.

Let us turn now to his treatment of the *Gryphaea* aspect of his article. Evidently he has made adequate collections and measurements of this genus, enough to serve for satisfactory statistical treatment. He takes for his index of the degree of coiling the length of the periphery which he tells us " is measured from the distal edge of the attachment area " (p. 100). This latter character, he says, is " nearly always less than 2 mm. in diameter ". My own numerous measurements (Swinnerton, 1939) on *Gryphaea incurva* show that rather more than 40 per cent of my specimens have areas greater than 2 mm. and they range up to as much as 25 mm. No doubt he would suggest that I had a bias towards collecting large areas, though he tells us that the general tendency is towards collecting small areas. Be that as it may, for most people

" nearly always " signifies something up to 90 per cent or over. For Hallam it may apparently be only about 60 per cent, or at any rate above 50 per cent. I agree with him that the area is a possible source of error in measuring the periphery and that the error due to an area of only 2 mm. is negligible. Unfortunately he leaves us completely in doubt as to whether or not he did measure those grypheas with areas larger than 2 mm., which must make up some 40 per cent of his material. If he did measure them how did he allow for size of area ? Without this information it is impossible to assess the value of his figs. 2 and 3 as evidence against Trueman's conclusions.

Let us now turn from the morphological aspect of his statistical inquiry to the field and stratigraphical aspects. As already suggested one of the struts in Hallam's thinking is an obsession about bias in collecting. He carefully exonerates himself from sinning in this respect, but holds the view that bias played a part in the collecting done by others. On page 106 he goes so far as to accuse Trueman of " highly selective collecting " in favour of there being a " gryphaeoid trend up the succession ". He has never seen Trueman's collection, much less studied it. Apparently he has not taken the trouble to search out and examine other collections made under Trueman's guidance. He does not appear to have sought out, examined, and collected from Trueman's original collecting site or locality. He cannot therefore possibly have any other basis for making this statement than his own biased imagination. Trueman's custom was to make his collection, study them carefully, then, and then only, did he formulate his conclusions. Hallam, on his own showing, starts off with " serious doubts " while as yet he is in the field collecting. He was, therefore, at the outset in just that state of mind which induces selective collecting. But as already noted he exonerates himself from bias.

Trueman and his followers have all been scrupulously careful in making their collections, and have kept closely to certain precise requirements generally recognized by palaeontologists as essential if sound and reliable progress is to be made in solving evolutionary problems. Briefly summarized, these are: that (*a*) specimens should as far as possible, be collected from precisely defined levels, bed by bed ; (*b*) those from each bed, being penecontemporaneous, must be kept separate and must on no account be mixed ; (*c*) those from each locality must also be kept separate and not mixed. Anyone wishing to follow in the tracks of these workers can do so easily for in their papers they give the essential details of the localities visited. Thus, for example, Maclennan and Trueman (1942) tell us that their specimens were collected " at a horizon near the top of the Broadford Beds, at a point on the west shore of Loch Aline, just south of an old jetty ". Anyone, therefore, can go straight to the spot where they did their collecting.

Hallam's statistical results are depicted graphically in his figs. 2 and 3. The specimens represented in fig. 2, he tells us, were collected from the *angulata* zone of Dorset, Somerset, Glamorgan, and Yorkshire. Those for fig. 3 came from Glamorgan and Skye. All these areas are sufficiently large and indefinite to give the impression that he is afraid lest anyone should find his sites and test his collecting. His measurements on his specimens are recorded in each figure in the form of an elongated cluster of dots representing, not one collection from a specific locality but 4 and 2 collections respectively, made at widely separated and unspecified localities. No one with the slightest understanding of the variational and geographical problems involved in the study of evolution would ever dream of lumping collections together in this indiscriminate manner. The clear rays of truth which will emerge from the careful study of carefully made collections become completely lost when collections are mixed in this way. They are as completely lost as the bright colours from a paint box are lost when they are mixed. As with these, the mixture takes on the colour and clarity of mud.

With fig. 3 Hallam sins even more grievously. In addition to mixing collections from these widely separated and unspecified localities he just as lightheartedly mixes collections from two distinct subzones. Such a monstrous method of constructing statistical figures could only have been devised by a person to whom space and time have no significance for the elucidation of evolutionary problems. Such then is the person who accuses Trueman of "highly selective collecting". He does so simply because his own conclusions, based upon an extraordinary lack of evidence and an unbelievable jumbling of specimens, badly localized and inadequately examined, do not accord with those or Trueman and other workers.

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The Stromatoporoid genus *Milleporella* Deninger

By R. G. S. Hudson

(PLATE VII)

Abstract

The holotype of the stromatoporoid *Milleporella sardoa* Deninger, 1906, from the Senonian of Sardinia is redescribed and the genus *Milleporella* Deninger, 1906, and the family Milleporellidae Yabe and Sugiyama, 1935, are redefined. A new superfamily the MILLEPORELLICAE, is founded.

THOUGH the hydrozoan *Milleporella* Deninger, 1906, is the nominate genus of a family, it lacks precise definition since *Milleporella sardoa* Deninger, 1906, its type species, was founded with inadequate description and illustrations, and has never been redescribed. Nevertheless, in 1920, Yvonne Dehorne, in her great monograph on the Mesozoic Stromatoporoidea, described two new species of *Milleporella*, which genus she considered to be a hydrozoan but not a stromatoporoid since its reticulum consists entirely of vertical lamellae and transverse laminae. These two species thus founded were *Milleporella marticensis* Dehorne, 1920, holotype from Senonian of Martigues, Bouches-du-Rhône, France, and *Milleporella adriatica* Dehorne, 1920 (= *Istriactus adriaticus* Munier-Chalmas gen. et sp. MS. in coll.), holotype from Bakowiza, Trieste, from beds considered to be Lower Eocene by Munier-Chalmas, Dehorne (1920) and Lecompte (1952, 1956), and ?Upper Cretaceous by Kühn (1928) and Steiner (1932). Since these are the only two species adequately described, recent diagnoses of the genus are based upon them and not on the type species and therefore, as noted by Lecompte (1952, p. 28), should be accepted with reservation. The holotype of the species is now in the collections of the Geologisch-Palaontologisches Institut of the University of Freiburg and is here redescribed. It has been lent to the author by the courtesy of Professor Pfannenstiel. The author also records his thanks to Dr. E. Flugel who informed him of its location.

Order **STROMATOPOROIDEA** Nicholson and Marie, 1878

Superfamily MILLEPORELLICAE nov.

Diagnosis.—Stromatoporoids with clinogonal skeletal tissue.

Included families.—Milleporellidae Yabe and Sugiyama, 1935; Parastromatoporidae fam. nov.; Milleporidiidae Yabe and Sugiyama, 1935.

Family MILLEPORELLIDAE Yabe and Sugiyama, 1935

Milleporelloids Yabe and Sugiyama, 1930, p. 23.
Milleporellidae Yabe and Sugiyama, 1935, pp. 152, 158; Lecompte, 1952, p. 25; 1956, p. F138; Galloway, 1957, p. 457.
Millestromidae Hudson, 1953, p. 885.
Milleporelloidae Alloiteau, 1952, p. 392.

Nominate genus.—*Milleporella* Deninger, 1906. Other genera.—*Millestroma* Gregory, 1898; *Stromatoporellina* Kühn, 1927.

Diagnosis.—Stromatoporoids with reticulum of vertical lamellae formed of clinogonal-fibrous pillars joined by lateral extensions and enclosing open or closed monomorphic coenospaces and/or coenotubes. Astrosystems, variously developed, of axial astrotubes with radial, horizontal or inclined, lateral tubes. Transverse laminae and tabulae may be present, variously developed.

Genus MILLEPORELLA Deninger, 1906

Milleporella Deninger, 1906, p. 66; Dehorne, 1920, p. 98; Kühn, 1928, p. 86; Yabe and Sugiyama, 1930, p. 27; Steiner, 1932, p. 83; Yabe and Sugiyama, 1935, p. 159; Kühn, 1939, p. A47; Lecompte, 1952, p. 28; Alloiteau, 1952, p. 393; Lecompte, 1956, p. F138.[1]
Istriactis nom. nud. Munier-Chalmas, MS. in coll. (see Dehorne, 1920, p. 99).

Type species (monotypic).—*Milleporella sardoa* Deninger, 1906. *Other species.*—?*Stromatopora virgiloi* Osimo, 1910; *Milleporella marticensis* Dehorne, 1920; *M. adriatica* Dehorne, 1920; all from Turonian or Senonian.

Diagnosis.—Genus of Milleporellidae with vertical lamellae, transversely angular-vermiculate and enclosing polygonal coenotubes and/or elongate, irregular coenospaces both of fairly constant width. Laminae at various intervals. Individual tabulae in astrosystems only. Astrosystems, variously developed, of axial astrotubes and lateral canals.

Milleporella sardoa Deninger, 1906

Plate VII, figs. 1–3

Milleporella sardoa Deninger, 1906, pp. 66–68, pl. 7, figs. 8a, b; Dehorne, 1920, p. 98; Kühn, 1928, p. 86; Steiner, 1932, p. 83.
Milleporella ichnusae Deninger, 1906, explanation of pl. 7, figs. 8a, b.

Holotype.—Specimen 8 and thin sections D, E, and F. Senonian (with *Hippurites cornuvaccinum* Bronn), near Nuraghen della Mandra, Southern Nurra, Sardinia.

[1] Fig. 112 (3), p. F139, in Lecompte (1956) should be titled *Milleporidium* and not *Milleporella* and should be placed in the Milleporidiidae and not the Milleporellidae; fig. 111 (4b), p. F137, should be titled *Milleporella* and not *Milleporidium*, should be numbered 5b, and referred to as *Milleporella adriatica*; fig. 111 (5), p. F137, should be numbered 5a: it is printed upside down.

Diagnosis.—*Milleporella* with nodular coenosteum. Pillared vertical lamellae (pillars 0·075–0·1 mm. across ; connecting lamellae 0·05–0·075 mm. across) transversely angular-vermiculate and bounding irregular elongate coenospaces (0·125–0·20 mm. across) or occasionally enclosing coenotubes. Astrosystems, indefinite though common, consist of axial astrotubes (up to 0·3 mm. across) with a few irregularly radial unwalled lateral tubes (0·2 mm. across). Laminae (0·025 mm. thick) irregularly spaced (very generally about 0·5–0·7 mm. apart). Tabulae, only in astrosystems, rare. Clinogonal fibrous tissue very fine.

Structural details.—The coenosteum is nodular and not latilamellate: its surface is not known. It was presumably slightly mamellate since the laminae, usually considered to be parallel to the coenosteal surface, rise to form low hummocks where they approach the astrosystems.

The reticulum is composed entirely of vertical lamellae formed by pillars and connecting lamellae ; these latter are formed by vertically continuous transverse outgrowths from adjacent pillars meeting and amalgamating to form a wall joining the pillars. These connecting lamellae have at intervals small pore-like openings. In transverse section, the vertical lamellae form a labyrithine pattern of coenospaces with slightly wider coenotubes scattered throughout. The laminae, which are aligned tabulae, are continuous and fairly level, but frequently overlapping. They were of subsequent growth to the lamellae which pass through them. Non-aligned tabulae do not occur except rarely in the astrotubes. The axial astrotubes are vertically continuous though their vertical extent is not known. The lateral tubes are short and vaguely radiate outwards and downwards from the axis of the astrosystem : they have no vertical extension. The astrosystems are generally indefinite since both vertical and lateral tubes have no walls and the axial astrotubes may be open.

The skeletal tissue of the pillars and connecting lamellae consists of very fine, evenly sized, granular calcite, variously dark, cloudy or clear, often forming very fine fibres (0·003 mm. across) which are vertical in the axial part of the pillar, but curve outwards and upwards at about 45° to its periphery. There are no evident " centres of calcification ". The most evident fibres appear to be tubular and are of clear calcite about one calcite grain thick. The tissue of the laminae is dark non-fibrous granular calcite.

The Definition and Systematic Position of *Milleporella*

The above definition of the genus *Milleporella* is based on the cited species. There are, however, two genera, *Millestroma* Gregory, 1898 (type species : *Millestroma nicholsoni* Gregory, 1898 ; holotype from

Turonian, Egypt) and *Stromatoporellina* Kühn, 1927 (type species: *Stromatoporella haugi* Dehorne, 1917; lectotype from Senonian, Martigues, France) which are similar to *Milleporella* and might, by a widening of the concept of that genus, be included in it. *Millestroma* was, in fact, redescribed by the author (Hudson, 1953) and considered to be so similar to *Milleporella* as then understood that it was stated to be a senior synonym of that genus. Re-examination of *Milleporella sardoa* has shown, however, that its reticulum consists of atabulate coenospaces and laminae whereas that of *Millestroma nicholsoni* consists of tabulate coenotubes, differences which can legitimately be considered of generic rank.

The genus *Stromatoporellina* was founded by Kühn with a much wider connotation than the structural characteristics of a single species. In 1927, he called attention to the difference in the structure of the skeletal tissue of the Palaeozoic and Mesozoic hydrozoans, the latter then generally allocated, as by Dehorne (1920), either to *Stromatopora* or *Stromatoporella*, both Palaeozoic genera. The pillars and transverse lamellae of the Mesozoic forms were, he considered, built of individual trabeculae composed of fibres radiating upwards and outwards from the trabecular axis. Such tissue structure, he claimed, did not exist in Palaeozoic forms. He, therefore, grouped the Mesozoic "*Stromatopora*" under a new genus *Stromatoporina* and the Mesozoic "*Stromatoporella*" under a new genus *Stromatoporellina* choosing as type species *Stromatoporella haugi* Dehorne.[1] The clinogonal tissue which is the diagnostic basis of Kühn's new genera, is shown here to be also characteristic of *Milleporella sardoa*. *Stromatoporellina haugi*, recently redescribed by Lecompte (1952, 1956), has a reticulum composed of vertical lamellae mainly bounding vermiculate coenospaces and astrosystems of axial astrotubes and lateral canals, both important diagnostic features of *Milleporella*. It differs from that genus by the absence of laminae, by its tabulate coenospaces and coenotubes and by the more clearly defined lateral branches of its astrosystems. Though clearly structurally related to *Milleporella*, its differences can be provisionally considered to be of generic value.

The genus *Milleporella* has been placed in various groups within the Hydrozoa. In 1928 and 1939, Kühn, in his systematic synopses of the hydrozoans, accepted *Milleporella* as a stromatoporoid and

[1] In 1958, Madame A. Schnorf-Steiner founded a genus *Astrorhizopora* with *Stromatoporella haugi* Dehorne as the type species. Her genus is thus a junior objective synonym of *Stromatoporellina* Kühn, 1927. She also founded the genus *Emscheria* with *Emscheria nerthensis* Schnorf-Steiner as the type species. This species (figured by Lecompte, 1952, pl. 2, fig. 2, and 1956, text-figs. 108, 1a, 1c as *Stromatoporellina haugi*) differs little from *Millestroma nicholsoni* Gregory, 1898, the type species of its genus. *Emscheria* Schnorf-Steiner, 1958, is therefore, in the opinion of the author, a junior subjective synonym of *Millestroma* Gregory, 1898.

placed it in a heterogeneous family group into which he collected all *Stromatopora*-like Mesozoic hydrozoans. Yabe and Sugiyama (1930), however, following Dehorne, still considered *Milleporella* to be distinct from the stromatoporoids and placed it, with their new genus *Tosastroma*, in a hydrozoan group which they called the Milleporelloids. This group, enlarged to include *Milleporidium* Steinmann and *Millestroma* Gregory, was accepted by Steiner (1932), but was reallocated to the Stromatoporoidea. Yabe and Sugiyama (1938) agreed with this allocation and redefined their group as a family, the Milleporellidae, adding the genus *Siphostroma* Steiner but excluding *Milleporidium*. This family was accepted, but with different connotations, by Alloiteau (1952) and Lecompte (1952, 1956). The three genera, *Milleporella*, *Millestroma*, and *Stromatoporellina*, are linked by the common possession of clinogonal tissue, a reticulum formed by vertical lamellae, tabulae and/or laminae, and by astrosystems of axial astrotubes and offset lateral tubes. Such structural features should, in the opinion of the author, define the family Milleporellidae. *Siphostroma* Steiner and *Tosastroma* Yabe and Sugiyama lack astrosystems and *Siphostroma* and possibly *Tosastroma* have orthogonal tissue : they should not, therefore, be included in the Milleporellidae as by Yabe and Sugiyama (1935) and Lecompte (1952, 1956).

Many Mesozoic stromatoporoids have, like the Milleporellidae, clinogonal skeletal tissue and a reticulum of vertical lamellae. Two of these genera, *Parastromatopora* Yabe and Sugiyama, and *Steinerella* Lecompte, have been included in the Milleporellidae by Lecompte (1956) and the question arises as to whether they should not all be included in that family. There is, however, a marked difference in the structure of their astrosystems : in the genera of the Milleporellidae the astrosystems still retain radial horizontal lateral tubes forming horizontal or inclined tubes within the reticulum ; in other genera the radial structures of the astrosystems are radial narrow corridors (astrocorridors) vertically continuous within the reticulum. This distinction excludes *Parastromatopora* and comparable genera from the Milleporellidae. They are therefore grouped in a new family, the Parastromatoporidae. Nevertheless, the two families are closely linked and form part of a morphological series in general trending towards a coenosteum entirely of vertical elements, and an astrosystem in which the astrorhizal pattern is replaced by individual astrotubes or autotubes, all members of the series being linked by clinogonal skeletal tissue. The trend ends in the Milleporidiidae, a family which has often been considered hydroid but not stromatoporoid (Kühn, 1939 ; Hudson, 1956). Whatever its relationship to the Hydroidea, it is evidently also closely akin to the Stromatoporoidea and since its members occur both geologically and geographically with the main

development of the Mesozoic stromatoporoids, it is convenient to group them in the Stromatoporoidea. This morphological series, consisting of the Milleporellidae, the Parastromatoporidae, and the Milleporidiidae, forms a taxonomic unit in the Stromatoporoidea and, for their reception, the superfamily, the MILLEPORELLICAE, is here constituted.

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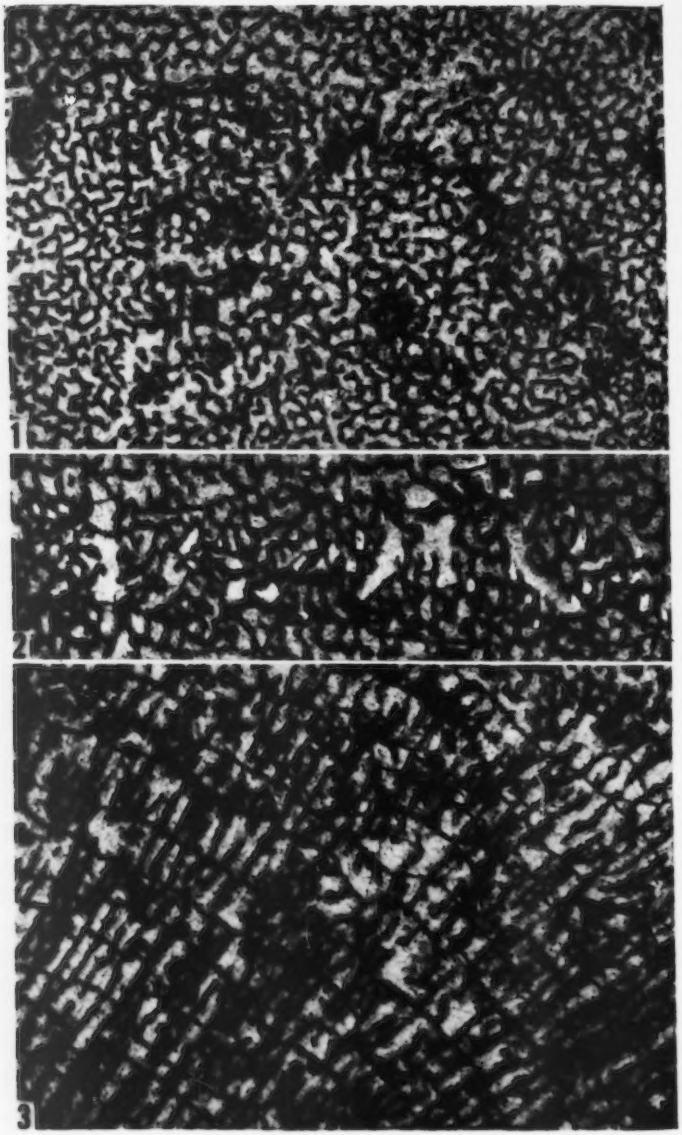

Milleporella sardoa DENINGER

EXPLANATION OF PLATE VII

Milleporella sardoa DENINGER. THIN SECTIONS E, F, × 12, OF HOLOTYPE, SPECIMEN 8, COLL. GEOLOGICAL-PALAEONTOLOGICAL INSTITUTE, UNIVERSITY OF FREIBURG. SENONIAN, SOUTHERN NURRA, SARDINIA.

FIG. 1.—Transverse section F; darker coloured areas are sections of laminae. Wider and more open spaces are lateral tubes of astrosystems.

FIG. 2.—Oblique section, F; wider vertical space in left is an axial astrotube; those on right are lateral tubes.

FIG. 3.—Radial section, E; showing vertical pillars, connecting lamellae with pores, and laminae.

CORRESPONDENCE

THE GROWTH AND FORM OF BRACHIOPOD SHELLS

SIR,—I should like to congratulate Dr. M. J. S. Rudwick on his recent paper, " The growth and form of brachiopod shells " (Rudwick, 1959) and express appreciation of his analysis of the different components involved in their growth. I cannot agree, however, with his statement that dimensions such as length, breadth, and height of the shell form an unsuitable basis for statistical analysis. His statement appears to be founded on three points. There is undoubtedly an element of truth in each, but I shall attempt to demonstrate that each contains an element of misconception which has, I believe, led him to draw a false conclusion.

(1) It is true that statistical analysis based on the frequency distribution of the ratio of height and length may fail to discriminate between two species of brachiopod which demonstrably differ in the profile of the shell. But it is not true that in statistical treatment they " would be regarded as identical in this character ", because it is fundamental in the logic of statistical comparison that absence of a significant difference does not prove identity. It is true that statistical comparison has sometimes been misused in this respect, but only an illogical statistician would really consider that he could prove identity. The absence of a significant difference may be used to supplement qualitative observations that also fail to reveal a difference, but in such a case, the possibility always remains that further statistical analysis using larger samples might reveal a difference. Statistical analysis is an ideal tool for those seeking differences between populations, but it cannot be used to demonstrate identity.

(2) In the case of a species which changes during ontogeny from a gently convex to a highly convex shell, it is true that a frequency distribution graph of the ratio between height and length might show a bimodality, when a high proportion of young shells is present in the sample. But even in the absence of a thorough qualitative examination of shell forms, it is not true that " this bimodal distribution would certainly be taken to reveal the presence of two species ". It is unlikely that a statistician would jump to this conclusion because it is well known that bimodality may be produced in a number of different ways and that the interpretation of such graphs has many pitfalls (Joysey, 1956). The frequency distribution method was used in some of the earliest applications of statistical analysis to palaeontology, but it has now been generally abandoned in favour of relative growth studies. If the relative growth method were applied in the case cited by Dr. Rudwick the difficulty which he has described would not be encountered. If one plotted a graph of height against length the resulting scatter diagram would indicate the relationship between the young and adult stages of each species in a mixed assemblage. It would be possible to fit a trend line to the scatter diagram of the young stages of each species and use the slope and intercept of these lines as a basis of statistical comparison.

(3) It is true that dimensions such as length, breadth, and height of a brachiopod shell are each a complex resultant of many different growth components, and that any particular magnitude may have been produced by any of an infinite number of different growth patterns. It is also true that these dimensions cannot adequately express the subtly complex shell forms of brachiopods. But to conclude that these dimensions are unsuitable for statistical analysis involves a *non sequitur* in the argument, because it is not intended that they should even attempt to describe the many different growth components of which they are a product. The inherent complexity of a biological dimension does not destroy its reality. The dimensions of a brachiopod shell are characters in their own right, and are amenable to statistical analysis which may be used to detect differences between populations.

The application of statistical methods to palaeontology is still in its infancy, and some of the methods which were used in the earlier studies were incorrectly applied. Many recent studies give the impression that a sledge-hammer

is being used to crack a nut, because they are largely concerned with the development and trial of new techniques. Although still based on such simple dimensions as length, breadth, and height of the shell these new techniques have already overcome the difficulties described by Dr. Rudwick, and so it is certainly premature to reject these dimensions as a basis for statistical analysis.

On a broader issue, there is at present a tendency for palaeontologists to prefer either qualitative or quantitative methods and to follow one almost to the exclusion of the other. In consequence, they sometimes have an incomplete appreciation of the available evidence relating to a problem, and are liable to become engaged in controversies which have no valid basis. The final solution of any problem must satisfy the evidence derived from all sources. In the field of palaeontology, I believe that qualitative and quantitative methods should not be regarded as alternative to each other, but rather as supplementary to one another.

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SIR,—I am grateful to Dr. Joysey for his comments on my critique of the use of parameters in brachiopod statistics and I welcome the opportunity to clarify the position.

(1) In the first case, it is true that a competent statistician would regard the shells as " not significantly different ". But if he is more than a competent statistician—if he is a palaeontologist competently using statistics for a palaeontological purpose—he must necessarily go beyond his judgment as a statistician and interpret the absence of statistical difference in palaeontological terms. This involves his judgment as a palaeontologist, which is logically discontinuous from his judgment as a statistician. It is my contention that the absence of any significant statistical difference is liable to be interpreted as a morphological identity in the character, and thereafter as a taxonomic identity of the shells. This is not a question of good or bad statistics, but of good or bad palaeontological judgment.

(2) I hope that Dr. Joysey's cautionary comments on the use of frequency distribution graphs, in the paper to which he refers, will help to raise the standards of the statistics used by palaeontologists. But even the use of a scatter diagram would fail to eliminate the ambiguities and confusions that I described. The adults of the two species would still be grouped indistinguishably together in the same part of the scatter ; and the young of the second species would occur in a scatter separate from the corresponding adult shells and separate from the young of the first species. Certainly it would be possible to fit trend lines to these different scatters ; but the palaeontological *meaning* of the lines could be established only by comparing the scatter diagram with the actual shells, that is, by a qualitative study of shell form. This would reveal the metamorphosis undergone in the ontogeny of the second species, and hence would lead to a true interpretation of the trend lines. The example I used in my paper was of course an extreme case ; and probably no palaeontologist would in practice fail to notice the great difference in form between the two shells described. But the application of statistics, using the final length, breadth, and height of the shell as parameters, is liable to lead to analogous false interpretations even when the differences in shell form are less immediately obvious. A more fruitful application of

quantitative method would be to plot the changes in certain parameters during the ontogeny of many individual shells, deriving a separate curve from each shell. This would make the differences between the shells graphically apparent, and would be the quantitative analogue of the " dynamic " modes of description which my paper was designed to advocate ; but it would not be, strictly, a statistical technique.

(3) It is true, of course, that *any* parameters can be used as a basis for statistics, regardless of their ontogenetic derivation. But, as in the other points, we are concerned with the palaeontological interpretation of the statistical results, not with the competence or incompetence of the statistician. The question at issue is again one of palaeontological judgment : are statistics based on these particular parameters so far divorced from the mode of growth of the shells, and so far abstracted from the observable shell forms, that they are liable to overlook or to obscure the palaeontologically significant relationships ? Certainly *any* parameters will give *some* statistical results ; but do these particular parameters lead to palaeontologically significant results ?

It is my belief that the only basis for adequate palaeontological judgment is a thorough qualitative knowledge of the shell forms ; and that this knowledge should not only govern the interpretation of the statistical results, but should also determine beforehand which of all possible parameters are most suitable for systematic discrimination. I have no wish to disparage the use of statistics or to deny their usefulness in their proper place, but only to affirm their true status as a technical tool in palaeontology, and as methodologically subordinate to qualitative studies. The present fashion for statistics is undoubtedly beneficial in so far as it encourages quantitative precision wherever that is possible ; but it is pernicious in so far as it sometimes leads to disparagement of the unquantifiable element in the discernment of systematic differences.

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